

UTILIZATION OF SYNTHESIS GAS GENERATED FROM AGRICULTURAL WASTE AS CLEAN SUSTAINABLE FUEL

Muhammad Roslan Rahim^a, Annisa Palupi Trisasongko^a, Mastura Ab Wahid^a, Mohammad Nazri Mohd Jaafar^{a,b,*}, Norazila Othman^b, Mazlan Said^c, Puad Elham^d, Mahanim Sarif@Mohd Ali^d

^aFaculty of Mechanical Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia

^bUTM Aeronautics laboratory, Institute for Vehicle System & Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia

^cInstitute for Noise and Vibration, Faculty of Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia

^dBiomass Technology Programme, Forest Products Division, Forest Research Institute Malaysia (FRIM), 52109 Kepong, Selangor, Malaysia

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*Corresponding author

nazrijaafar@utm.my

Graphical abstract



Abstract

Increased energy source demand has been the current driver of Malaysia's economic growth. Renewable energy is therefore included in Malaysia's energy policy to diversify its energy resources. With 77% of Malaysia's land directed for agriculture – particularly for palm oil plantation, biomass from agriculture industries is thus considered as a viable energy resource. In addition to palm oil plantation, 18.56 million hectares of Malaysia's tropical forest contributed substantial wood waste from logging activity. Through gasification, these resources can produce syngas. This paper aims to demonstrate the potential of palm kernel shells (PKS) and wood waste (WW) to generate syngas using a downdraft fixed bed gasifier, which has a suitable oxidation zone temperature to support syngas production. Results showed that PKS and WW syngas consisted of 94.93% and 97.92% carbon monoxide (CO) respectively with low hydrogen (H₂) gas contents. The lower heating values (LHV) from PKS and WW are 10.68 MJ/kg and 10.26 MJ/kg, respectively. It can be concluded that agricultural wastes such as PKS and WW had shown high potential to become an alternative source of energy in the form of syngas.

Keywords: Renewable Energy, Biomass, Palm Kernel Shell, Wood waste, Syngas

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1.0 INTRODUCTION

Hydrocarbon sources have continuously been used to sustain modern living – exhausting the world's current reserves. The price of hydrocarbon also continues to fluctuate, went at the highest in 2016 at about USD97.98 per barrel and the lowest was in 2020 at USD39.16 per barrel for Texas Sweet crude oil [1]. Deleterious impacts of petroleum usage on the environment can be observed. For instance, air quality around the world has declined rapidly – affecting human health. Alternative energy sources from biomass may be able to reduce adverse effects of petroleum product usage. Amongst various biomass sources,

agriculture waste has yet to be fully utilized, Therefore, agriculture wastes are targeted as a potential candidate for renewable, sustainable and environmentally friendly source of energy.

Biomass conversion through gasification yields syngas. Biomass gasification is considered as an alternative technology, as it allows the usage of a wide variety of biomass sources such as the forest and agricultural wastes into energy. Its main product, syngas, is a combustible fuel which can be used for various applications [2, 3]. Carbon monoxide (CO) and hydrogen (H₂) are the primary components of syngas [4]. Typically, syngas contains 40% carbon monoxide (CO), 25% - 30% hydrogen (H₂),

and up to 5% methane (CH₄), which are considered combustible gases, whereas non-combustible gases (inert gases) consist mostly of nitrogen (N₂) and carbon dioxide (CO₂). These compositions, however, can vary between feedstocks and are influenced by the gasification process along with its operating conditions [5, 6].

The feasibility of a feedstock as an alternative fuel can be determined through several parameters such as its solid fuel calorific value; syngas composition, characteristics, and calorific value; and gaseous emission concentration. Other parameters such as temperature profiles during gasification process and flame profile are also thought to be important parameters during gasification, as they determine the produced gas quality. Results from this work are compared between the materials used, which are PKS and WW, to ascertain the quality of the syngas generated from the gasifier used in this work.

1.1 Higher Heating Value, HHV (Solid Material)

Solid fuel quality can be determined through its calorific value. Biomass, unlike coal, possess a lower energy density, which affects its performance in producing energy. Calorific value of biomass is influenced by its moisture content. High moisture is predominantly found in green biomass and waste materials. Aside from moisture content, fixed carbon, according to Özyuguran and Yaman [7], is also closely associated with calorific value as it positively impacts the energy possessed by the biomass. However, other parameters such as high volatile matter, does not necessarily translate to higher calorific value, as volatile matter contents are generated from non-combustible gases. Aside from that, ash content has both inert effects on calorific value and poses detrimental effects on heat gained during combustion. Reduction of calorific value can be attributed to ash formation as the process requires energy, and thus absorbs energy produced through combustion. Other factors may also contribute to calorific value of biomasses, however, these remain unknown. The method used to determine the calorific value of this solid is in accordance with the standards set by BS EN 14918: 2009. Bomb calorimeter can be used to accurately determine calorific value with good precision [8].

1.2 Proximate Analysis (Solid Material)

Moisture, ash content and volatile matter can be quantified through a method called proximate analysis. Combustion and gasification performance is influenced by the feedstock's moisture. Increased moisture content may hinder the ignition of biomass feedstock, particularly in the form of pellet or briquette.

Volatile matter is another parameter determined in proximate analysis, whereby high volatility results in reduced decomposition and reaction temperatures [9]. Cai et al. [10] further added that high volatile matter in agricultural waste signifies increased reactivity. Subtracting the original mass of the feedstock from the sum of moisture, volatile matter and ash content yields fixed carbon content.

Thermochemical energy conversion efficiency is determined through the overall gasification process, consisting of pyrolysis and controlled gasification to produce char. Pyrolysis, or carbonization, refers to the removal of non-carbon species to produce porous fixed carbon (char). Final temperature, residence time and heating rate are amongst the contributing

factors towards carbonation, particularly when carried out in a rotary kiln or multi hearth furnace. When tar is decomposed, the porous structure of char becomes partially filled with irregular carbon, leading to low adsorption capacity. The combustion process thus requires semi controlled gasification using steam, carbon dioxide, or a mixture of both [11, 12, 13]. Similar process can also be found in proximate analysis, which allows proximate analysis to act as an influential factor towards thermochemical conversion.

1.3 Ultimate Analysis (Solid Material)

Elemental contents of feedstock can be determined through ultimate analysis. This method is able to determine percentages of C, H, N and S, which enables the prediction of syngas composition and emission. Prediction of syngas composition and emission is considered important as it is useful for environmental impact study. Aside from predicting syngas composition, understanding the elemental contents allows researchers to predict the combustion performance.

1.4 Gas Characteristics

Elemental composition and syngas heating value variability has led to significant challenges in practical combustion system application. The gas composition is influenced by feedstock composition such as water content and plant type, process reaction temperatures and gasification process in a certain gasifier reactor.

1.5 Gas Composition

Syngas consists of gases that can be divided into two major categories: combustible and non-combustible gases. Examples of combustible gases include CO, hydrogen (H₂), methane (CH₄) and other hydrocarbon gases. On the other hand, gases such as CO₂ and N₂ are considered non-combustible. Norafzanizam et al [14] elaborated that H₂ and CO contribute to 50% of the total energy that syngas possesses whilst the remaining energy is contributed by CH₄ and (aromatic) hydrocarbons. This implies that the lower heating value of syngas varies depending on its composition. For instance, higher concentration of the non-combustible gases results in lower LHV. Many aspects contribute towards LHV such as feedstocks, gasification method and temperature.

1.6 Gaseous Emissions

Producer gas (syngas) obtained through gasification can be fed into a combustor to estimate its combustion and emission performance. Evaluating emissions from syngas combustion is important as it aids in understanding the degree of pollution. In the experiments, emissions such as NO_x, CO, and CO₂ were measured, and special care were instituted to detect any harmful gases. The measurements were carried out using online gas analyzer Horiba Enda 5000, whose accuracies are up to ±0.01% mass ratios.

This paper demonstrates the study of syngas quality from agricultural waste and its correlations with parameters influencing their quality.

2.0 METHODOLOGY

The experimental set up can be broken down into five major steps. The steps are: (i) materials preparation; (ii) calorific value, proximate and ultimate analysis estimation; (iii) test rig set up; (iv) syngas characterization; and lastly, (v) emissions profile including flame analysis from syngas combustion performance.

2.1 Material Preparation

Meranti wood waste (WW) and palm kernel shell (PKS) were used as the materials in this research, as displayed in Figure 1. Samples are dried at 32–36°C for waste wood and 45°C for palm kernel shell to ensure low moisture. A small portion of the overall samples are taken to create a feedstock powder used to analyze its calorific value. The remaining materials were divided into two categories according to the rig used. Feedstocks should be around 5cm for downdraft gasifier, whilst fluidized bed requires the feedstocks to be smaller than 5mm.

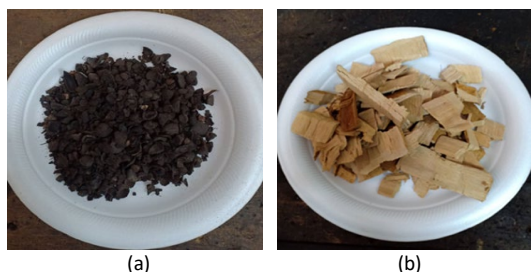


Figure 1 Biomass materials used in the experiments: (a) Palm kernel shells, and (b) Waste wood meranti.

2.2 Calorific Value, Proximate And Ultimate Analysis

The calorific value, proximate and ultimate analysis of the feedstocks were determined using powdered feedstocks, illustrated in Figure 2. Figure 3 displays an overview approach used during proximate analysis.

Prior to conducting the gasification work, about 10g of each agricultural wastes samples, were crushed to powder-size, sieved and placed in a crucible and put inside the bomb calorimeter located in the Combustion Lab of Universiti Teknologi Malaysia (UTM). This technique is used to determine the calorific value of feedstocks. Inside the bomb calorimeter, the sample was burned with excess oxygen, and the combustion temperatures were recorded with increments of 0.01°C. powder-sized samples were also sent to UTM Chemical Engineering Lab for ultimate analysis. A CHNS/O Elemental Analyzer was used according to ASTM D5373 standard [13], as it is the best method to measure the chemical contents or the ultimate analysis of a biomass material. Results are expressed in percentage of mass, on a moisture free basis. In order measure the percentages of C and H, about 0.2 g of each sample are burned and subjected to a steam of pure oxygen. C and H of the charcoal were converted into CO₂ and H₂O respectively.



Figure 2 Test materials in powdered form for Proximate and Ultimate analysis.

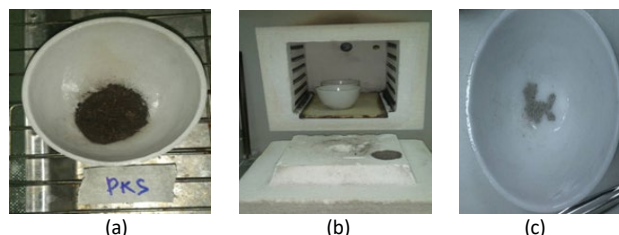


Figure 3 Feed stock preparations for Proximate and Ultimate Analysis: (a) Samples of feedstock; (b) Heating of sample in oven; and (c) Sample of feedstock after drying.

During gasification, produced gas was directed to tubes of KOH and CaCl₂. Weight increments observed on these tubes were then determined. Identifying nitrogen concentration can be done by using a flask containing concentrated H₂SO₄ and K₂SO₄ and mixing them with 1g of charcoal sample. Excess KOH is then added as the solution gains clarity.

The solution undergoes distillation once ammonia was released, and a known volume of acid solution is added and mixed with the solution. A back titration process, with the help of NaOH, was conducted to determine the remaining acid. Through this process, the liberated ammonia concentration can be quantified. On the other hand, the washings produced from the charcoal used in the bomb calorimeter can be used to determine sulphur concentration, as the process was able to produce sulphate from sulphur. The product produced from the aforementioned process were then mixed with barium chloride solution, which produced barium sulphate precipitate. The precipitate was filtered, washed and heated respectively, until constant weight was achieved. The percentage of sulphur can be determined using equation 1.

$$\text{Percentage of S} = \frac{32 \times m_{BaSO_4}}{233 \times m_{PKS}} \quad (1)$$

Proximate analysis of each sample was conducted by utilizing a furnace with a high precision mass balance. Basu [12] believed that the E-870-06 is a suitable standard to conduct proximate analysis for solid fuels such as wood, which has been overtaken by ASTM E-870-82. Furthermore, Basu [12] emphasized that different standards should be used to analyze different components. Therefore, ASTM E-872 is used to estimate volatile matter of the feedstock. Ash content utilized ASTM-D-1102 and for the moisture content of woody samples using the ASTM E-871 standard, but for fixed carbon it can be determined through different methods [13]. To measure the moisture content, powdered sample was put in a crucible (without lid) and placed in the oven at 108 ± 2 °C. The sample was then cooled to room

temperature and weighed. Weight loss observed in this step represents moisture. To measure volatile matter, powdered sample was put in a crucible with lid and heated in a furnace at $900 \pm 15^\circ\text{C}$. The sample was then cooled and weighed. The weight loss signified the moisture and volatile matter contents. A bushel burner was used to heat the remaining samples to ensure all of the carbon contents were burned. Residues produced from this process is ash. Finally, subtracting the sum of moisture, ash and volatile matter content from 100% dry weight yielded the fixed carbon content.

2.3 Rig Set Up

The experimental schematic diagram is shown in Figure 4. A fixed bed gasifier (DG 50 open top downdraft gasifier) is used as a rig. The gasifier is equipped with an axial swirler, with type-K thermocouples capable of measuring a maximum temperature of 1200°C . The gasifier is 1000mm in length, open-ended and used mild steel for the combustion chamber. The combustion chamber is insulated with hy-cast cement, a Midi temperature data logger, an LCA 6000 air speed indicator and a digital camera. These tools were used to record wall temperatures. Emission profile were explored using HORIBA Enda 5000 gas analyzer. Figure 4 also illustrates the positioning of the gas sampling unit. Air supply from a blower is varied to simulate fuel rich and air-rich combustion.

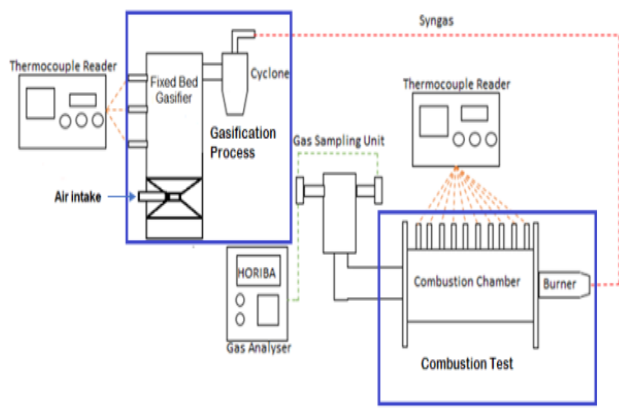


Figure 4 Schematic diagram of experimental rig set up

2.4 Gas Characterization

Gas characterization was carried out to determine gas composition and its properties. Figure 5 shows the gas sampling method. Tar removal set up is required to ensure syngas are free from contaminants such as tar and char. This set up includes ice and ice box.



(a)



(b)



(c)

Figure 5 Photographs showing the processes for: (a) Gas cleaning process, (b) Gas sampling, and (c) Tar sampling.

There are 6 impingement bottles required for tar removal. Bottles 1, 2, 3, and 4 were filled with 100ml of isopropanol and bottles 5 and 6 were loaded with silica gel. A separator was used to divide the ice box into two areas, where one area is filled with ice maintained at -15°C . This area is used to store impingement bottles 1–4, whereas the other area, maintained at 20°C , is used to store bottles 5 and 6. The bottles were equipped with an outlet that connects them to an auxiliary vacuum pump. Producer gas were directed to the tar removal system before stored in Tedlar bags. The syngas samples were sent to UTM Chemical Lab to determine its composition.

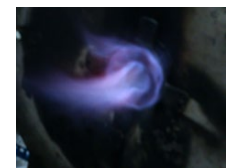
3.0 RESULTS AND DISCUSSION

3.1 Combustions Test, Flame and Emissions

Figure 6 shows the flame formation from combusting the generated syngas, produced from different feedstocks, in a gas burner attached with combustor chamber. Figure 6(a) shows a short and blue flame produced when combusting syngas from palm kernel shell (PKS). This flame had the highest temperature profile (600°C) during the combustion process of the syngas in the combustion chamber. Meanwhile, Figure 6(b) shows the flame produced when combusting syngas from wood waste, in which flame was less bright and purple yellowish in color rather than bright blue, which indicates lower temperature generated (587°C).



(a)



(b)

Figure 6 Flame formation in a gas burner when combusting different syngas from several feedstocks: (a) Syngas from palm kernel shell; and (b) Syngas from wood wastes.

Maximum temperatures observed in both flames were attributed to carbon monoxide in the syngas. Syngas composition and heating value was also seen to influence the size and shape of the flame. Aside from carbon monoxide content, flame temperatures are also affected by the volume fraction of non-combustible gases such as N_2 , H_2O and CO_2 . Increasing volume fraction of hydrogen in syngas will maximize the gas temperature, whereas decreasing temperature is where maximum volume fraction of inert gas level in syngas will be observed [15]. Yellowish flame colour appears when a primary air ratio is low. From visual observation, the colour for this flame

looks purplish with some yellowish flame. This yellowish flame is continuous and affected by the presence of solid carbon particles, and the fuel-air mixture was concluded to be rich [16, 17]. The flame also is longer compared to the syngas from PKS. On the other hand, a shorter flame with blue color indicates higher flame temperature, which would reduce the formation of NO_x and CO emissions [18]. The NO_x and CO concentrations emitted during combustion process are 7ppm and 10ppm for syngas produced by PKS, while syngas from wood waste contributed 9ppm and 12ppm, respectively which are generally low.

The second flame (Figure 6 (b)) was similar to that of laminar flame condition. Laminar flame is formed if the velocity of that flame front travels at relatively slower than the unburned gas in the normal direction to the flame surface. Laminar flame is prone to flashback and blow off, and thus undesirable in combustion systems. At the same time, it influences other fundamental combustion characteristics including flame spatial distribution [19].

When syngas heat reaction rate increases, laminar flame velocity is high. This occurs due to high levels of hydrogen. Moreover, high carbon dioxide and nitrogen dilution in the syngas fuel leads to higher laminar flame velocity. The value of laminar flame velocity also takes into account the mixture of hydrogen and carbon monoxide, thus are available to diversify the operating condition by changing the ratios such as fuel, air or equivalent ratio [20-25].

3.2 Proximate and Ultimate Analysis and Calorific Value

Proximate analysis showed that agricultural waste contains high concentration of carbon. Carbon can, in theory, be transformed into heat energy through thermal reaction. Higher levels of ash were found in PKS sample, at 10.68%. This is higher than that of wood waste (0.92%). A comparison was also made with the results of experiments conducted by Kaniapan, et al. [26], where the result of ash from his experiment was 4.75%, while the results of the study from Ukanwa, et al [27] showed that the percentage of ash was 1.10%.

Significant carbon content was found in agricultural waste despite its low hydrogen concentration. Higher carbon concentration may lead to higher calorific value, which is deemed desirable. Volatile matter concentration is mostly associated with hydrogen content, whereby most hydrogen is found to commonly bind with oxygen to form water. The water content lowers the calorific value of fuel, thus deeming the feedstock source of lower quality.

Nitrogen content was found to be minute in both samples. Due to its inertness, nitrogen does not contribute any useful effects on the calorific value of the fuel. Sulphur concentration of both samples were significantly low, despite significant concentration of oxygen content observed. Oxygen in solid fuel may decrease the calorific value of the fuel. High moisture is attributed to high oxygen content in feedstock. In addition, it indicates low calorific value and low coking power. Oxygen within a feedstock coexists with hydrogen, which lowers the concentration of hydrogen further. A 1.7% decrease in calorific value may occur with a 1% increase of oxygen concentration in the feedstock [28]. This is also mentioned by Pham [29], where an increase in oxygen content between 10 to 20% leads to the decrease of 12% in caloric value. The dependency of calorific value on the oxygen content was also demonstrated by

Dermibas, [30], where the reduction in calorific value occurs when the oxygen level increased. Table 1 shows the comparison of the parameter values from the proximate and ultimate analysis between PKS and WW.

Table 1 The proximate and ultimate analysis results, and CV results of PKS and WW.

Properties	Feedstock		
	Palm kernel shell	Wood waste	
Moisture content (% wet basis)	8.25	10.23	
Volatile matter	63.76	79.16	
Proximate analysis (wet % dry basis)	Fixed carbon	17.31	9.69
	Ash	10.68	0.92
	Carbon	34.07	43.69
Ultimate analysis (wet% dry basis)	Hydrogen	3.35	6.33
	Nitrogen	0.86	1.96
	Sulphur	0.09	0.05
	Oxygen (by different)	50.95	47.05
	Higher Heating Values (HHV) (MJ/kg)	22.3	17.94
Lower Heating Values (LVH) (MJ/kg)	10.68	10.26	

3.3 Syngas Characterization

Figure 7 summarizes the syngas composition from both feedstocks. The experiment shows that an oxidation zone should be above 900°C to produce syngas. This syngas, known as pure-CO syngas, consists of 94.93% and 97.92% of CO for PKS and WW respectively. The amount of H₂ contents which are 0.023% and 0.042%, respectively, are considered very small [31]. This leads to low LHV of the syngas, compared to H₂ rich gaseous fuel. Multiplying each element's LHV with the combustible gas composition (H₂, CO and CH₄) yields the LHV of the fuel. H₂ concentration in syngas has shown to significantly impact the life of the hot section of a gas turbines engine. In this case, the syngas that was produced, if it was to be used as fuel for a gas turbine engine, will produce a lower flame temperature due to the lower H₂ content. This means, it would not harm the present engines built with present technologies to withstand standard fossil fuels [32].

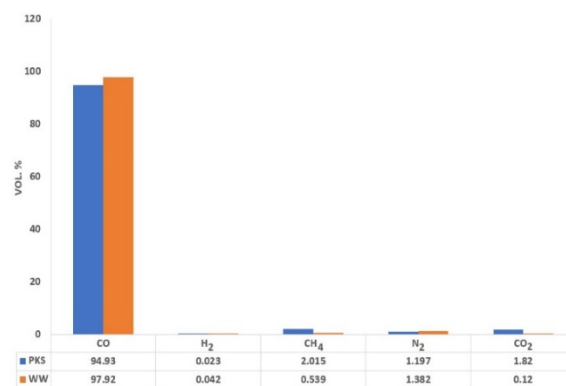


Figure 7 Comparison of syngas composition between PKS and WW.

4.0 CONCLUSION

Based on the experimental study conducted, syngas can be obtained from agricultural wastes through gasification process using a gasifier. The agricultural wastes were found to have high potential to replace traditional fossil fuels. The agricultural wastes were identified as potential feedstocks that could contribute to the energy sector categorized as renewable energy source. These palm kernel shell and wood agricultural wastes could be combusted in gasifiers to produce pure-CO syngas that is composed of 94.93% and 97.92% CO, with small amount of H₂ content of 0.023% and 0.042%. This means that the downdraft gasifier that was used in these experiments is capable of converting high energy carbonaceous solids into syngas. The syngas derived from these agricultural wastes displays prospective ability to be used as an alternative fuel for power generation, transportation fuels and chemical production.

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