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Assessing the Technical and Environmental Potential of Coconut Shell Biomass: Experimental Study through Pyrolysis and Gasification

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Abstract: Biomass-derived fuel is a promising candidate for future bioenergy, which will reduce CO₂ emissions and reliance on fossil fuels. Physicochemical analysis, pyrolysis, and gasification processes were conducted to study the potential of coconut shell biomass. According to the findings, coconut shell biomass includes numerous important components, and the temperature affects both the characteristics of the charcoal, and the syngas composition. The lowest temperature generates the most charcoal (41.85%), whereas the highest temperature produces the most energy (32 MJ/kg). At the maximum temperature, a good gas composition was obtained (14.15% H₂, 15.22% CO, 13.98% CO₂, and 10.13% CH₄ concentration, respectively).

Keywords: Biomass; Charcoal; Gasification; Pyrolysis; Syngas

1. Introduction and motivation

The importance of green energy and energy policies become an interesting alternative for power generation from biomass waste¹. This was attributed to the fact that the release of carbon dioxide (CO₂) from fossil fuels contributes considerably to climate change², hence the need for advanced fuel technologies in the short term for alternate power generation³. Biomass is the world's greatest renewable source of carbon that can be used to move away from fossil fuels. Biomass is any hydrocarbon material containing a high proportion of carbon, hydrogen, and oxygen, as well as a lesser quantity of nitrogen, sulphur, and fiber⁴. Now, biomass is the amplest and cheapest fuel material for biofuels production, that will allow climate change mitigation and decrease the dependence on fossil fuels. One of the most significant sources for producing hydrogen gas (H₂) is predicted to be biomass⁵. The most promising biomass feedstocks for energy production originate from agriculture, forestry, and industry. Agricultural waste is in abundance, at a relatively low cost. Malaysia has a positive energy trade balance and promising biomass productivities due to the increasing production of palm-based agricultural goods. It has the capability of utilising renewable energy resources to

augment the country's limited petroleum and coal supplies.

Coconuts (*Cocos nucifera L.*) are the fruits of coconut trees that grow in a variety of soils. They are most commonly found on sandy and saline beaches along the coast^{6, 7}. Coconut is grown on about 10 Mha in 92 countries, with Asian countries accounting for 75% of global output⁸. Numerous coconut fruits are produced annually by the coconut palm trees⁹. The growing global demand for coconut fruit makes the coconut industry have great value worldwide. Malaysia was rated as the world's 12th largest producer of coconuts¹⁰ with a volume of 517.6K tonnes. Coconut stands as the 4th largest cash crop in line with oil palm, rubber, and rice in Malaysia. The market for coconuts grows as palm oil prices fall, causing its price to increase¹¹. In Malaysia, the coconut business is only getting started, and demand is growing. Many benefits are derived from the coconut fruit for foods, health, and beauty^{11, 12}. As a result, coconut businesses create a large amount of biomass waste, such as coconut shells and husks. The factual abundance of biomass shows the quantity of residue that can be used¹³ for power generation. As a result, the biomass from coconut shells is easily available for power generation. Furthermore, coconut shell has a high lignin content⁸, and high volatile matter¹⁴, this makes it suitable for charcoal and syngas

production.

The most common utilization of biomass is the traditional burning for domestic purposes, which remarkably leads to negative environmental issues¹⁵. Thermochemical or biochemical conversion processes are the vital routes for biomass conversion into energy without much damage to the environment. In thermochemical methods (combustion, pyrolysis, gasification, and liquefaction), heating the biomass at a specified condition generates power source¹⁶. Thermochemical conversion serves as a favorable technology for biomass conversion and upgrading. The energy content of a given biomass can be exploited more intensively when transformed into useful fuel by pyrolysis and gasification processes. The pyrolysis process is the first step in any thermochemical conversion technique that includes decomposing biomass in an inert environment to generate a carbonaceous solid residue (charcoal/biochar), condensable (biooil and water biooil) and non-condensable vapor (gases). Charcoal is a highly carbonaceous solid substance with a high energy content, similar to high-rank coals that are utilised for a variety of applications. The pyrolysis process changes the structure and percentage of the charcoal significantly. The primary factor influencing the composition and production of the charcoal product has been found to be temperature¹⁷. Gasification is a thermochemical process that uses air or steam to convert biomass into syngas at high temperatures (700°C or higher). The synthetic or producer gas is used as a power source in boilers, furnaces and pyrolysis reactors; for production of chemicals, and other gaseous fuels such as the production of hydrogen⁴. Gasification efficiency is among the gasification process variables, that is primarily affected by the amount of gaseous fuel contained in syngas, like H₂ and CO. Gasification includes complicated chemical processes and is affected by numerous elements such as gasifier design, fuel characteristics, gasifying agent, operating parameters such as gasifying agent flow rate, gasification temperature, pressure, equivalency ratio, and so on¹⁸.

Analyzing the biomass through a physicochemical process is required to impart the thermochemical pyrolysis and gasification mechanism. To evaluate the effectiveness of the thermochemical conversion, it is essential to comprehend the thermal decomposition of fuel¹⁹. The physicochemical behaviour of biomass dictates the choice of conversion technology²⁰. Moisture and ash content are considered during thermochemical processes. They affect the product by lowering the heating value. The ash, which is present in the form of metal oxides that do not evaporate during the thermochemical reaction, typically changes the nature of the charcoal and the composition of the gases²¹. The calorific value obtained from biomass predicts the value of the fuel²². The more the energy content in the biomass, the more it would yield a high value fuel. The physicochemical characterization of biomass has many important aspects of sustainable development which

include carbon storage, biodiversity, and climatic regulation. Hence, a thorough analysis of how biomass's physicochemical characteristics affect energy processes is essential. This will provide the detailed potential of coconut shell biomass since each type of biomass is derived from a variety of plants with unique chemical composition. It is essential to investigate the amounts of elements in lignocellulosic materials that might be released all through the gasification and pyrolysis processes.

The use of coconut shell biomass for gasification and pyrolysis processes, primarily to produce coconut shell charcoal and syngas, has received relatively little research. There are insufficient details to characterize the technologies currently used in the production of coconut shell charcoal, along with empirical research on the production process of coconut shell charcoal. Therefore, it is crucial to look at the biomass's characteristics as well as how well it performs in the thermochemical process before it is applied in industries. This study aims to investigate the biomass fuel properties for various thermal conversion processes of thermogravimetric analysis, ultimate analysis, and energy content. Furthermore, the behaviour of temperature on the charcoal properties (charcoal's yield, energy content, moisture content, and ash content) and the producer gas (gas composition, carbon conversion efficiency, heating value, and solid yield) from pyrolysis and gasification was investigated. The suitability of the biomass fuel for the pyrolysis or gasification process via energy conversion efficiency was also calculated.

2. Characterization and experimental process

2.1 Preparation

Coconut shells from a local store in Seri Iskandar, Perak, Malaysia were used in this experimental study. They were separated from the meat and fibrous sheath, pounded with a hammer, and sieved using sieve analysis to the required size. A grinder was used to grind the sample into a powdered form for the characterization process. It is important to characterize the raw material to evaluate its composition before the thermochemical process²³. The experiment was carried out in the biomass laboratory, Universiti Teknologi PETRONAS. The sample was dried in accordance with the ASTM E871-82 standard²⁴. The bomb calorimeter was used for the energy content of the biomass and the charcoal samples. The moisture content was calculated by:

$$MC\% = \frac{\text{Initial weight} - \text{Final weight}}{\text{Initial weight}} \times 100 \quad (1)$$

2.2 Proximate and ultimate test

The proximate analysis describes the amount of moisture, volatile matter, fixed carbon, and ash being readily available in a fuel. A thermogravimetric analyzer

was employed in accordance with ASTM E1131-08²⁵⁾ standard for the analysis. The peaks in the TGA graph of biomass mass loss with temperature were used to calculate the amounts of the properties in the biomass. The ultimate test analysis was conducted using ASTM D3176-09 to evaluate the elemental components of carbon, nitrogen, hydrogen, and sulfur by weight percent²⁶⁾ using CHNS-932 standard technique and oxygen by calculations.

2.3 Quality parameters

The moisture content, energy value, and ash content are the quality parameters of biomass and charcoal. An IKA C-6000 calorimeter was used to measure the energy content of the coconut shell biomass and coconut shell charcoal in accordance with ASTM D4809-18 standard procedure²⁷⁾. The moisture content was obtained with ASTM E871-82²⁸⁾, and ASTM E1755²⁹⁾ for the ash content. The quantity of heat generated by a unit volume of syngas during combustion is known as the calorific value of the syngas under normal circumstances³⁰⁾. It was obtained by Eq. 2:

$$\text{HHV}_{\text{syngas}} = 12.63X_{\text{CO}} + 12.74X_{\text{H}_2} + 39.82X_{\text{CH}_4} \quad (2)$$

where the high heating value of CO, H₂, and CH₄ were 12.63 MJNm⁻³, 12.74 MJNm⁻³ and 39.82 MJNm⁻³, respectively. X_{CO} , X_{H_2} and X_{CH_4} and represent their respective volumetric percentages in the dry producer gas, respectively.

2.4 Charcoal and syngas yield

The yield of the charcoal was expressed as weight percentages of the charcoal recovered to that of the biomass. The charcoal yield was calculated according to 31):

$$n = \frac{(M_c - \text{Mash.c})}{(M_{\text{dry.b}} - \text{Mash.b})} \times 100\% \quad (3)$$

where M_c is the mass of the charcoal (kg), $M_{\text{dry.b}}$ is the mass of the oven dried coconut shell biomass; Mash.c and Mash.b are the ash contents (kg) of the recovered coconut shell charcoal and the coconut shell biomass feedstock, respectively.

The syngas yield (Y) of the producer gas was calculated by:

$$Y = \frac{Q_a \times 0.79}{W_b \times N_2\%} \text{ Nm}^3 \text{ kg}^{-1} \quad (4)$$

where Q_a represents the air flow rate in Nm³hr⁻¹, and W_b , is the mass flow rate of the biomass in kg hr⁻¹. The dry syngas's nitrogen content, as determined by difference, is N₂%. 0.79 was assumed to be nitrogen and 0.21 oxygen, respectively.

2.5 Carbon and energy conversion efficiency

As stated by Taba *et al.*³²⁾, the carbon content of the gases CO, CO₂, and CH₄ is used to calculate the carbon conversion efficiency (η_c):

$$\eta_c = \frac{Y(\text{CO}\% + \text{CO}_2\% + \text{CH}_4\%) \times M_c}{22.4 \times C\%} \times 100\% \quad (5)$$

where Y is the syngas yield in Nm³kg⁻¹, the percentages of the respective gases (CO, CO₂, and CH₄) are expressed as CO%, CO₂%, and CH₄%, respectively. The atomic mass of carbon atom, and the mass percentage of carbon obtained in the biomass feedstock are represented as M_c and $C\%$, respectively. 22.4 is constant (vol. of an ideal gas).

The energy conversion efficiency depends on the usefulness of the output. The output energy to input energy ratio is used to calculate it.:

$$n_{\text{energy}} = \frac{\text{Output energy}}{\text{Input energy}} \times 100\% \quad (6)$$

Figure 1 (a) gives the general outline of the experimental methods. Figure 1b, 1c and 1d present the particle size of the coconut shell used for the physicochemical, pyrolysis and gasification experiments.

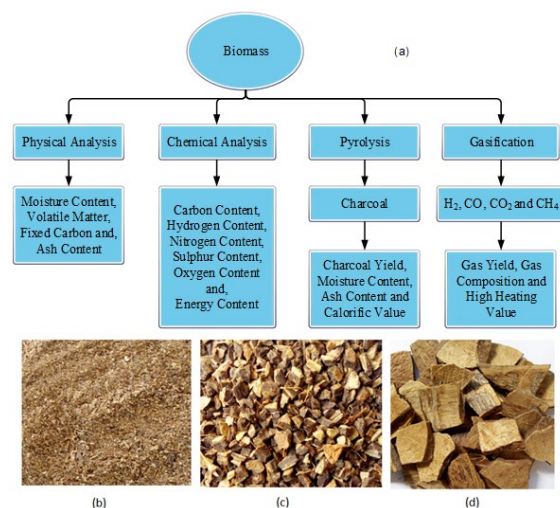


Fig. 1: (a) Experimental outline for characterization, pyrolysis and gasification process, coconut shells sample (b) powdered, (c) 2.5 mm particle size, and (d) 17.5 mm particle size.

2.6. Experimental

For both the pyrolysis and gasification tests, an electrically heated downdraft reactor system was utilized, together with a gas analyzer, temperature control, air, and nitrogen gas (Figure 2). Carbonization, also known as slow pyrolysis, was performed after removing all volatiles with a nitrogen gas purge at a flow rate of 2 bars. The reactor was preheated to the desired temperature before being fed 100 g of 17.5 mm particle size coconut shell biomass from the top. Throughout the trials, it was heated and kept in the reactor for 60 minutes at various carbonization temperatures (300°C to 500°C). During the process, as the organic biomass start to break upon heating, it goes through a series of reactions that result in solid, liquid, and gas products. A condenser separates the condensable and non-condensable gaseous products. The condensable gases condense at the condenser, while the

non-condensable gases flow via the filter to the gas cleaning unit, and the concentrations of the primary syngas components are recorded by an online gas analyzer. After the experiment, the reactor was allowed to cool to collect the charcoal, which was then placed in an air tight container for further examination. To explore the viability of coconut shells for the gasification process, the gasification process used a particle size of 2.5 mm, rate of airflow at 3 L/min, and a temperature range of 700-900°C. The gas compositions were obtained from a computer connected to the gas analyzer (Emerson X-stream X2GP) via its interface Ethernet automatically for every second.

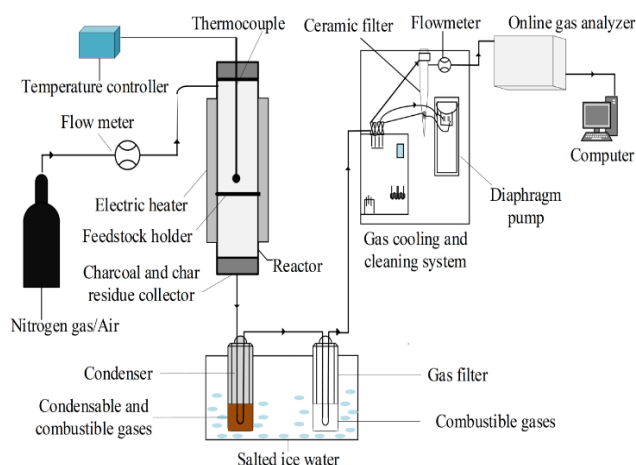


Fig. 2: Carbonization and gasification experimental setup.

3. Results and discussion

3.1 Proximate test and energy value

The proximate test findings were shown using data from a thermogravimetric investigation of coconut shell biomass. Figure 3 presents the mass loss of coconut shell with regards to the carbonization temperature. The content of moisture (Mc), fixed carbon (FC), ash, and volatile matter (VM) were obtained from the graph.

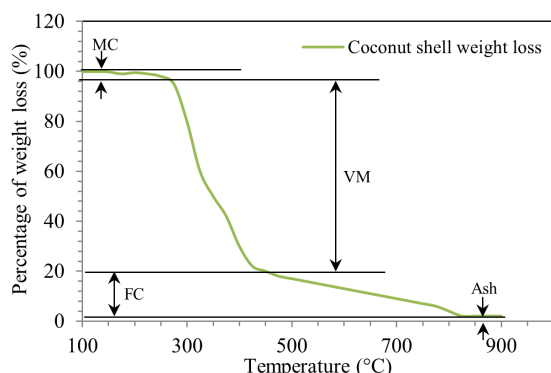


Fig. 3: Percentage weight loss of coconut shell biomass against temperature by thermogravimetric analysis.

The results of the physicochemical properties showed extreme variation among the coconut shell sample and different biomass residues as summarized in Table 1. The feedstock of the current study presents the highest fixed

carbon of 21.4%, while sugarcane bagasse has the lowest (8.3%). The volatile matter contents of the biomasses have higher values ranging from 82.55 wt.% for sugar cane bagasse to 58 wt.%. The moisture content ranges from 4% to 11.95%. Coal also has moisture content of 9.34%, a volatile matter of 25.68%, a fixed carbon content of 31.59%, and an ash content of 33.39%. Coconut shell presents the quantity of volatile matter to be higher, lower moisture value, and low ash value than coal³³. Coconut shell biomass is suitable to produce the solid carbon product. It has the highest fixed carbon among the biomasses. The ash value among the biomass changes significantly; with the lowest 1.14% date palm seed (DPS) and rice husk have the highest 24.63%. Low efficiency is caused by the high ash content in biomass, which results in poor thermochemical reactions³⁴. Coconut shells present this property in fewer amounts when compared to that of rice husk³⁵ and coal³³. Hence, pre-treatment for ash cation removal is not required before using coconut shell biomass for pyrolysis and gasification processes. The high volatile matter content in the coconut shell biomass clearly denotes the presence of H₂, CO₂, CO, as well as light hydrocarbons such as ethane, methane, and propane, etc.³⁴. Consequently, rapid pyrolysis of coconut shells is anticipated to result in excellent yields. When compared to other biomass, the amount of the properties obtained in the coconut shell biomass would address the sustainability need by employing the biomass as a possible feedstock for thermochemical processes. Furthermore, coconut shell with a low moisture content and, a high fixed carbon is recommended for charcoal and syngas production from thermochemical conversion of slow pyrolysis and gasification processes.

The greater a fuel's energy content, the more energy is released during the igniting process³⁶. The calorific value ranges from 13.76 to 22.63 MJ/kg as presented in Table 1. It differs from different biomass samples. In the current investigation, the calorific value of the feedstock was determined to be 20.33 MJ/kg greater than the value of coal, which is 16.16 MJ/kg³³. The calorific value of biomass typically falls between 15 and 20 MJ/kg, which is comparable to the calorific value of a low-rank coal³⁷. A high value of lignin in given biomass shows the suitability of the biomass to present high calorific value. Lignin is the hardest to thermally decompose and contain the highest amount of energy in a biomass³⁷. The energy content of the feedstock material of this study was found to be higher than the values of all the biomass presented in Table 1 including coal, except date palm seed and palm kernel shell (PKS). Thus, this supports the potency of coconut shell biomass as a biomass resource.

Table 1. Physicochemical characteristics of different biomass.

Biomass type	Proximate analysis				HHV (MJ/kg)	Ref.
	MC (%)	VM (%)	FC (%)	Ash (%)		
Coconut shell	5.8	71.58	21.4	1.2	20.33	This study
Coconut frond	11.95	62.37	17.76	7.92	15.22	³⁸⁾
PKS	4	58	43	4	20.4	³⁹⁾
OPF	6.15	80.55	16.43	3.02	17	¹⁴⁾
DPS	8.95	65.4	21.07	1.14	22.63	^{40, 41)}
Rice husk	8.4	65.33	10.04	24.63	13.76	³⁵⁾
Sugarcane bagasse	5.25	82.55	8.30	3.90	16.92	¹³⁾
Coal	9.34	25.68	31.59	33.39	16.16	³³⁾

3.2 Ultimate test

The ultimate test expresses the fundamental components found in biomass. It is essential in figuring out whether biomass is a suitable source of power for any thermal energy conversion. Table 2 shows the quantity of CHNS components found in coconut shells and other biomass. The carbon content (C) slightly varies among the biomasses. Date palm seed presents (28%) the lowest³⁹⁾ and palm kernel shell, (51%) the highest³⁹⁾. Coconut shells have a carbon content of 40% and coal has a carbon content of 72.15%. The nitrogen content ranges from 0.14% coconut frond³⁸⁾ and sugarcane bagasse¹³⁾ to 3% palm kernel shell³⁹⁾. Fuels with a nitrogen content (N) produce nitrogen oxides, which are toxic and unwelcome combustion byproducts (No_x). Some biomass containing the same amount of sulfur 0.09% sugarcane bagasse¹³⁾ and rice husk³⁵⁾ were found to have the lowest amount while coconut frond has the highest 0.54%³⁸⁾ content of sulfur (S). Coconut shell presents low amount of nitrogen 0.18% and sulfur 0.14% when compared to values of coal; 1.5% nitrogen and 0.89% sulfur content, respectively. The relatively minimum values of nitrogen and sulfur contents coconut shell biomass indicate minimum emissions of No_x and Sox in the gasification process. Hence, does not require any further filtration before utilization to reduce the emissions. Biomass with high nitrogen and/or sulfur results in a significant impact on operating outlay^{37, 42)}. Coconut shells possess considerably higher value of oxygen in comparison to coal and other biomasses from Table 2. As a result, there is less stoichiometric air demand for coconut shells during combustion⁴³⁾.

Table 2. Ultimate analysis of some raw biomass materials and coal.

Biomass type	Ultimate analysis					Ref.
	C (%)	H (%)	N (%)	S (%)	O (%)	
Coconut shell	40.03	5.26	0.18	0.14	54.39	This study
Coconut frond	40.02	6.03	0.14	0.54	53.27	³⁸⁾
PKS	51	7	3	0.48	39	³⁹⁾
OPF	42.60	5.71	0.42	0.29	51	¹⁴⁾

DPS	28.3	7.53	0.7	-	46.02	^{40, 41)}
Rice husk	31.6	5.2	0.7	0.09	37.79	³⁵⁾
Sugarcane bagasse	46.6	5.92	0.14	0.09	43.35	¹³⁾
Coal	72.2	7.19	1.55	0.89	18.21	³³⁾

3.3 Pyrolysis product distribution

Temperature affects the composition of the final product of any thermochemical conversion method. Figures 4 and 5 demonstrate how the reaction temperature had a significant impact on the yield, energy content, moisture content, and ash content of the coconut shell charcoal. At lower temperatures, the mass loss of the coconut shell biomass during pyrolysis occurred because of the volatile matter and water removal. As the process temperature was raised, the residual volatiles in the charcoal escaped, creating condensable gases, resulting in a reduction in yield. As indicated in Figure 4, the charcoal yield was decreased from 41.85% to 25.27%. This might be as a result of the significant percent mass loss at high temperatures, which leads to a decrease in the yield. This trend of declining yield with rising temperature is in line with findings from other studies^{30, 44, 45)}. The thermal reactions and formation of more volatile products cause the condensable and combustible products to increase moderately at elevated temperatures⁴⁶⁾. The energy content increases with temperature as shown in Figure 3 (28 MJ/kg to 32 MJ/kg). All of the charcoal properties differed due to temperature differences. 32 MJ/kg was found to be the highest calorific value at the highest temperature (500°C), and 28 MJ/kg at the lowest temperature (300°C). It has been established that a charcoal's energy content is influenced by temperature⁴⁾. This can support the assurance; energy compaction occurs solely in the organic portion of the feedstock biomass³¹⁾. Charcoal has a higher energy content than biomass feedstock. This resulted from the biomass being exposed to heat during the thermochemical conversion process that created charcoal⁴⁷⁾. As a result, raising the temperature increases the energy content of charcoal⁴⁸⁾.

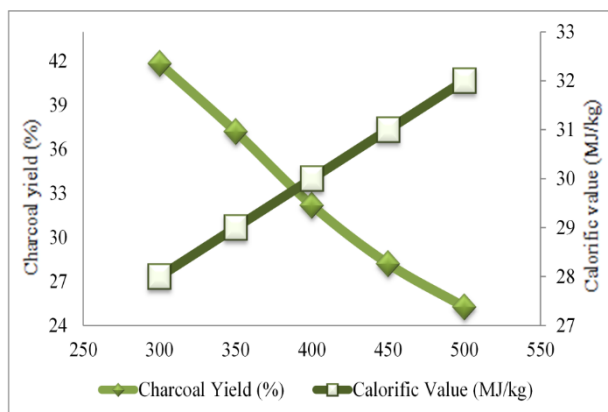


Fig. 4: Charcoal yield and calorific value versus different carbonization temperature.

The relationship between the moisture and ash content

of the recovered coconut shell charcoal and the carbonization temperature is shown in Figure 5. When the temperature was raised from 300 to 500°C, it was discovered that the ash content values increased from 1.01 to 1.09%. The increase of the ash content may be because of the rapid burning of the charcoal. At the elevated temperature of 500°C, ash particles were noticed physically on the charcoal, which was found to be 1.09%. Ash content value of 1.01% at 300°C was obtained. The trend in the charcoal moisture content decreases (1.65% to 1.09%) at elevated carbonization temperature (300-500°C). Higher temperature causes the devolatilization process rapidly. At the temperature of 450-500°C, the carbonization process is almost completed. The values of the ash and moisture are similar at these temperatures. Reaction temperature takes part in the thermal decomposition of biomass. The ideal temperature is necessary when the solid product is the needed biofuel. Higher temperature exposure to the biomass reduces the solid yield and facilitates other pyrolysis products^{4, 49}. Figure 6 presents the charcoal sample at different carbonization temperatures

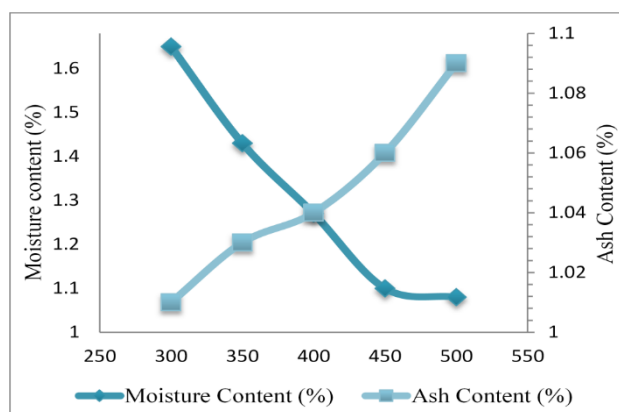


Fig. 5: Relation between carbonization temperature, moisture content and ash content of charcoal.

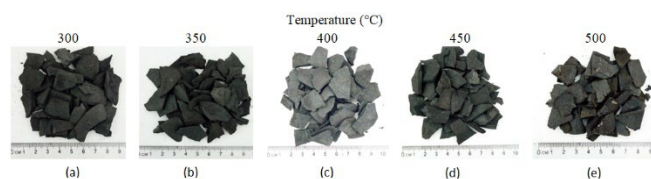


Fig. 6: Charcoal sample at different temperature.

3.4 Gasification products

The major syngas comprises of carbon monoxide (CO) and hydrogen (H₂) gas, followed by carbon dioxide (CO₂), methane (CH₄) and water. The average value of the volumetric composition of syngas for 840 seconds was used. During the process, the energy needed for the thermochemical reaction in breaking the bond in the coconut shells was by the heat released during partial oxidation. It also helps to increase the temperature of the syngas and drive away from the endothermic reactions⁴. The process temperature strongly influences the producer

gas composition (Figure 7). The carbon monoxide and hydrogen composition show an increasing trend at elevated gasification temperature. Carbon monoxide and hydrogen contents range from 11.03% to 16.8% CO and 8% to 14.35% H₂. However, the carbon dioxide and methane composition, reduce from 700 to 900°C range. The gas composition of CO₂ and CH₄ at the highest temperature was lower than those of CO and H₂ products. At higher temperatures, CO₂ and CH₄ decompose through dominating methanation (C + 2H₂ ↔ CH₄) reaction to form H₂ and CO gas. Furthermore, the boudouard reaction (C + CO₂ → 2CO) yielded a higher composition of CO and H₂. The productions of hydrogen lessen the methanation reaction which yielded low CH₄ content³⁰. Between temperature of 700 and 900°C, CO₂ decreased from 16.9% to 13% and CH₄ from 12.7% to 9.5%. The composition of the syngas is affected by the temperature, gasifying medium, and flowrate. Alina attested to this⁵⁰. While producing less CO₂ and CH₄ gases, the reactions produced more H₂ and CO gases³⁰. The gas composition trend agreed with the previously reported literature^{30, 43}. Relatively pure H₂ can be obtained from syngas produced due to the high amount of hydrogen gas present. Reactions involving water-gas shift and steam reforming make this possible.

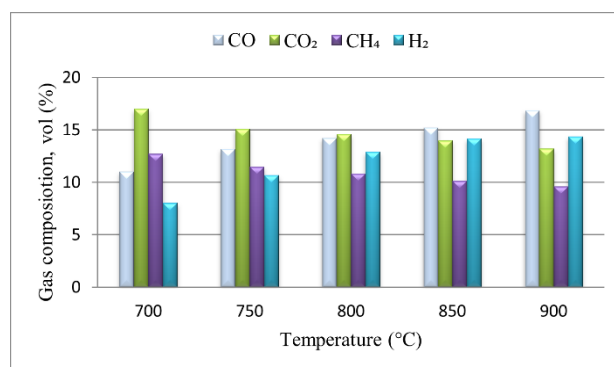


Fig. 7: The effect of the temperature on the syngas composition from gasification of coconut shell biomass.

The relation between the operating temperature, yield and higher heating content of the syngas was investigated as shown in Figure 8. The temperature has an influence on the biomass conversion process for product distribution, syngas yield, and energy efficiency⁴. The gas yield rises with rising gasification temperature at temperatures between 700 and 900 °C. At the highest temperature of 900°C, the maximum syngas yield of 1.44 m³/kg was obtained. This could be ascribed to the rising rates of the devolatilization reactions during the pyrolysis stage⁴³. A slight increase of 0.02 m³kg⁻¹ in the yield was observed at 850°C and 900°C temperatures. The lowest yield at 700°C calculated to be 1.29 m³kg⁻¹. The higher heating value was calculated based on the combustible syngas components. Hence it was found to increase from 7.47 to 7.76 MJNm⁻³ at elevated temperatures from 700 to 900°C with an increasing trend of the gases. On the yield and heating value of the syngas, an increase in temperature within a

restricted range had almost no impact. Obviously, the lower values of the gas higher heating content at lower temperatures could be the consequence of the reduction in carbon monoxide and a rise in carbon dioxide. The findings from literature⁵¹⁾ corroborate with the current results.

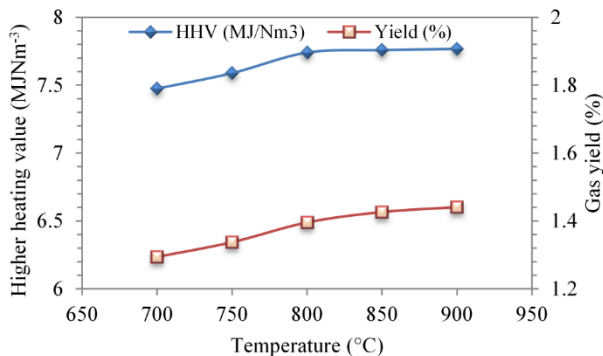


Fig. 8: The relation between the temperature, the gas yield, and the higher heating value.

The relationship between the gasification temperature, solid yield and the carbon conversion efficiency (CCE) of the synthetic syngas is shown in Figure 9. The CCE was calculated from the syngas composition and the feed data. It was observed at the studied temperatures; the factors considered have a substantial impact on the CCE. Carbon conversion efficiency slightly increases continually with the rising temperature from 70.52% to 76.35%. These findings were similar to the result in the literature⁵¹⁾. The solid yield decreases from 39% to 25% as the temperature rises. This is apparent from the fact that lower temperatures were insufficient to complete the decomposition of the biomass feedstock and the gas production.

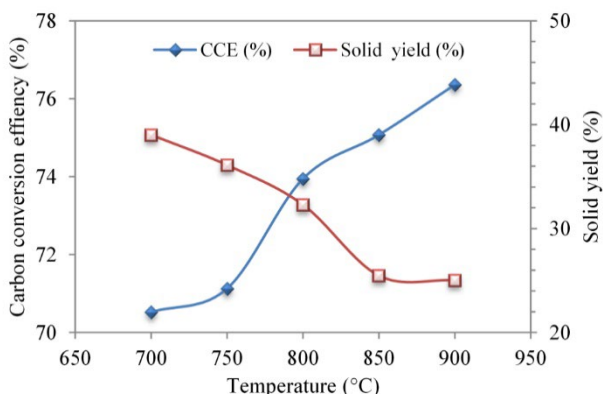


Fig. 9: Carbon conversion efficiency and solid yield versus the gasification temperature.

3.6 Energy conversion efficiency

The ratio of output power to input power is defined as energy conversion efficiency (ECE). Using the energy output of the product and the energy input of the biomass, the ECE of the coconut shell charcoal and the syngas were calculated at both the lowest and highest temperatures. For

the syngas product, the ECE was discovered to be highest at the highest temperature, whereas for the charcoal, it was highest at the lowest temperature. At 300°C and 500°C, it was determined to be 69.06% and 51.58%, respectively, while at 900°C and 700°C, it was calculated to be 57.69% and 49.86%. The ECE of charcoal was observed to be higher than that of syngas at both the highest and lowest temperatures.

4. Conclusions

The considerable availability of coconut shell biomass and its physicochemical characteristics merged with the results of pyrolysis and gasification processes led to the drawn conclusions. The coconut shell biomass was characterized for biofuel production to investigate its potential suitability for either pyrolysis or gasification technologies. The impacts of process temperature on charcoal and syngas quality characteristics were examined. Because of its low volatile and ash content, coconut shell biomass is ideal for pyrolysis and gasification operations. A carbonaceous substance would result from the high fixed carbon content. According to the findings of the elemental composition, coconut shell biomass is suitable for the pyrolysis and gasification processes, leaving little to no carbon footprint. The data of the comprehensive quantitative characterization will help in modelling, design, and optimization of the thermochemical technologies. The temperature affects the charcoal’s quality parameters. At the highest temperature (500°C), a higher calorific value (32 MJ/kg) and ash content (1.09%) were obtained, while the charcoal yield and moisture content were lower at the specified temperature, respectively. At higher temperatures, the predominant gas composition appeared to be H and CO, with smaller quantities of CH₄ and CO₂ produced. The results indicate that coconut shell biomass has the potential to be used in both pyrolysis and gasification methods. Its use will eventually resolve related disposal issues. Coconut shell charcoal can be used to produce environmentally friendly biofuels and other chemicals; the syngas can be used to generate electricity and to manufacture petrochemicals. products. The current findings suggest that the characteristics of the coconut shell charcoal and the gas composition may fluctuate significantly depending on the process condition.

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Reference

- 1) R. A. Moghadam, S. Yusup, W. Azlina, S. Nehzati and

- A. Tavasoli, "Investigation on syngas production via biomass conversion through the integration of pyrolysis and air–steam gasification processes," *Energy Conversion and Management* **87**, 670–675 (2014).
- 2) "Annual Energy Outlook 2015 (AEO2015) [http://www.eia.gov/outlooks/aeo/pdf/0383\(2015\).pdf](http://www.eia.gov/outlooks/aeo/pdf/0383(2015).pdf) (accessed September , 2019).
 - 3) A. Al-Mamoori, A. Krishnamurthy, A. A. Rownaghi and F. Rezaei, "Carbon Capture and Utilization Update," *Energy Technology* **5**, 834 – 849 (2017).
 - 4) P. Basu, *Biomass Gasification and Pyrolysis: Practical Design and Theory*. (Elsevier, Elsevier, The Boulevard, Langford Lane Kidlington, Oxford, OX5 1GB, UK, 2010).
 - 5) Y. Furutani, K. Norinaga, S. Kudo and J.-i. Hayashi, "Current Situation and Future Scope of Biomass Gasification in Japan," *EVERGREEN Joint Journal of Novel Carbon Resource Sciences & Green Asia Strategy*, **4** (4), 24-29 (2017).
 - 6) "How much does a coconut weigh?" (Reference.com 2019) <https://www.reference.com/world-view/much-coconut-weigh-5faa7de1113733e7> (accessed December , 2019).
 - 7) M. Anem, Coconut in Malaysia. *Anim Agriculture Technology*. Available: <http://animagro.blogspot.com/2011/09/coconut-in-malaysia.html>. (accessed November , 2019)
 - 8) I. Yerima, and M.Z. Grema, "The potential of coconut shell as biofuel " *The Journal of Middle East and North Africa Sciences* **4** (5), 11-15 (2018).
 - 9) D. Krzysztof, M. Krzysztof, H. Taras and D. Barbara, "Impact of grinding coconut shell and agglomeration pressure on quality parameters of briquette " *Engineering for rural development, Jelgava* **23**, 1884-1889 (2018).
 - 10) FAO, 2019. "Production of Coconut in Malaysia: Understand the global production of Coconut in Malaysia.," UN FAO: Food and Agriculture Organization., FAO2019, <https://www.tridge.com/markets/coconut-MY/production>, (accessed December , 2019)
 - 11) T. Z. Yun, Magazine online, 2019. "The Edge Markets ", The Edge Malaysia Weekly, Magazine online 2019, <https://www.theedgemarkets.com/article/agriculture-coconut-revival>, (accessed December , 2019)
 - 12) I. Anton, U. S. Latifah and D. I. P. Meity, 2017 .
 - 13) G. Marrugo, C. F. Valdés and F. Chejne, "Characterization of colombian agroindustrial biomass residues as energy resources," *Energy and Fuels* **30** (10), 8386-8398 (2016).
 - 14) M. Inayat, S. A. Sulaiman and M. Y. Naz, presented at the MATEC Web of Conferences, "Effect of Torrefaction Process on the Coconut Shell Energy Content for Solid Fuel ", **826**, pp. 1-7, online: AIP Conference Proceedings.
 - 15) L. R. Lynd, M. Sow, A. F. Chimphango, L. A. Cortez, C. H. B. Cruz and M. "Elmissiry, Bioenergy and African transformation". *Biotechnol Biofuels* **8** (1), 1-18 (2015).
 - 16) H. B. Goyal, D. Seal and R. C. Saxena, "Bio-fuels from thermochemical conversion of renewable resources: A review," *Renewable and Sustainable Energy Reviews*, **12** (2), 504-517 (2008).
 - 17) R. K. Ahmad, S. A. Sulaiman, M. Inayat and H. A. Umar, "Effects of Process Conditions on Calorific Value and Yield of Charcoal Produced from Pyrolysis of Coconut Shells" Singapore, 253-262 (2020)
 - 18) G. S. Kumar, A. Gupta and M. Viswanadham, "Sensitivity analysis and optimization of parameters for the gasification of high ash indian coal," *International Journal of Applied Engineering Research* **12** (18), 7184-7193 (2017).
 - 19) D. K. Seo, S. S. Park, Y. T. Kim, J. Hwang and T.-U. Yu, "Study of coal pyrolysis by thermo-gravimetric analysis (TGA) and concentration measurements of the evolved species," *Journal of Analytical and Applied Pyrolysis* **92** (1), 209-216 (2011).
 - 20) P. McKendry, "Energy production from biomass: overview of biomass," *Bioresource Technology*, **83**, 55-63 (2002).
 - 21) Y. Yuliah, M. Kartawidjaja, S. Suryaningsih and K. Ulfi, "Fabrication and characterization of rice husk and coconut shell charcoal based bio-briquettes as alternative energy source " in *International Conference on Biomass: Technology, Application, and Sustainable Development I, IOP Conf. Series: Earth and Environmental Science*, **65**, 1, pp. 1-9: (2017) IOP Publishing.
 - 22) R. K. Ahmad, S. A. Sulaiman, S. B. Yusuf, S. S. Dol, M. Inayat and H. A. Umar, "The influence of pyrolysis process conditions on the quality of coconut shells charcoal," *Platform: A Journal of Engineering* **4** (1), 73-81 (2020).
 - 23) M. Ayadi, S. Ahou, S. Awad, M. Abderrabba and Y. Andres, "Production of Biogas from Olive Pomace," *EVERGREEN Joint Journal of Novel Carbon Resource Sciences & Green Asia Strategy* **7** (2), 228-233 (2020).
 - 24) ASTM-E871-82, ASTM International, 1-2 (2013).
 - 25) ASTM-E1131-08, ASTM International (2014).
 - 26) ASTM-D3176-09, ASTM International, 1-4 (2015).
 - 27) ASTM-D4809-18, ASTM International, 1-10 (2018).
 - 28) A. E871-82, (2013).
 - 29) ASTM-E1755-01, ASTM International, 1-3 (2015).
 - 30) S. A. Sulaiman, M. Y. Naz, M. Inayat, S. Shukrullah and A. Ghaffar, "Thermochemical characteristics and gasification of date palm fronds for energy production," *Theoretical Foundations of Chemical Engineering*, **53** (6), 1083-1093 (2019).
 - 31) F. Ronsse, S. Van Hecke, D. Dickinson and W. Prins, "Production and characterization of slow pyrolysis biochar: Influence of feedstock type and pyrolysis conditions," *Bioenergy*, **5** (2), 104-115 (2013).

- 32) E. L. Taba, M. F. Irfan, W. M. A. W. Daud and M. H. Chakrabarti, "Fuel blending effects on the co-gasification of coal and biomass-A review," *Biomass and Bioenergy* **57**, 249-263 (2013).
- 33) H. Song, G. Liu and J. Wu, "Pyrolysis characteristics and kinetics of low rank coals by distributed activation energy model," *Energy Conversion and Management* **126**, 1037-1046 (2016).
- 34) S. Sohni, N. A. N. Norulaini, R. Hashim, S. B. Khan, W. Fadhullah and A. K. Mohd Omar, "Physicochemical characterization of Malaysian crop and agro-industrial biomass residues as renewable energy resources," *Industrial Crops and Products* **111**, 642-650 (2018).
- 35) J. F. Saldarriaga, R. Aguado, A. Pablos, M. Amutio, M. Olazar and J. Bilbao, "Fast characterization of biomass fuels by thermogravimetric analysis (TGA)," *Fuel* **140**, 744-751 (2015).
- 36) K. A. Motghare, A. P. Rathod, K. L. Wasewar and N. K. Labhsetwar, "Comparative study of different waste biomass for energy application," *Waste management* **47** (Part A), 40-45 (2016).
- 37) H. Sadig, S. A. Sulaiman, M. N. Z. Moni and L. D. Anbealagan, "Characterization of date palm frond as a fuel for thermal conversion processes," in *MATEC Web of Conferences. MATEC Web of Conferences, 2017, vol. 131, p. 01002: EDP Sciences*.
- 38) S. A. Sulaiman, R. Roslan, M. Inayat and M. Y. Naz, "Effect of blending ratio and catalyst loading on co-gasification of wood chips and coconut waste," *Journal of the Energy Institute* **91** (5), 779-785 (2018).
- 39) R. K. Liew, W. L. Nam, M. Y. Chong, X. Y. Phang, M. H. Su, P. N. Y. Yek, N. L. Ma, C. K. Cheng, C. T. Chong and S. S. Lam, "Oil palm waste: An abundant and promising feedstock for microwave pyrolysis conversion into good quality biochar with potential multi-applications," *Process Safety and Environmental Protection* **115**, 57-69 (2018).
- 40) M. Zainab, E. H. Ali and J. Y. Qimimg, "Date Palm (Phoenix dactylifera L.) Seed Characterization for Biochar Preparation," in *The 6th International Conference on Engineering, Project, and Production Management (EPPM2015)*.
- 41) E. Elnajjar, S. Hasan, S. A. Zuhair, S. A. Omari and A. Hilal-Alnaqbi, "Characterization and chemical composition of UAE date seeds," in *2018 5th International Conference on Renewable Energy: Generation and Applications (ICREGA)*, pp. 56-60 (2018).
- 42) C. Bibbiani, F. Fantozzi, C. Gargari, C. A. Campiotti, E. Schettini and G. Vox, *Agriculture, Agricultural Sci. Proc* **8**, 637-645 (2016).
- 43) N. Punsuwan, C. Tangsathikulchai and T. Takarada, "Low temperature gasification of coconut shell with CO₂ and KOH: Effects of temperature, chemical loading, and introduced carbonization step on the properties of syngas and porous carbon product," *International Journal of Chemical Engineering*, **2015**, 1-16 (2015).
- 44) R. Khanna, M. Ikram-Ul-Haq, R. Rajarao, R. Cayumil, A. Rawal, V. Sahajwalla and P. S. Mukherjee, "Novel multidimensional carbons from structural transformations of waste lignin: A low temperature pyrolysis investigation," *Fuel Processing Technology* **166**, 312-321 (2017).
- 45) A. F. Ridassepri, F. Rahmawati, K. R. Heliani, Chairunnisa, J. Miyawaki and A. T. Wijayanta, "Activated Carbon from Bagasse and its Application for Water Vapor Adsorption," *EVERGREEN Joint Journal of Novel Carbon Resource Sciences & Green Asia Strategy* **7** (3), 409-416 (2020).
- 46) D. Chen, A. Gao, Z. Ma, D. Fei, Y. Chang and C. Shen, "In-depth study of rice husk torrefaction: Characterization of solid, liquid and gaseous products, oxygen migration and energy yield," *Bioresource Technology*, **253**, 148-153 (2018).
- 47) M. Characteristics of wood and charcoal from eucalyptus clones," *Floresta e Ambiente* **25** (2018).
- 48) R. K. Ahmad and S. A. Sulaiman, "Carbonization of Coconut Shell Biomass in a Downdraft Reactor: Effect of Temperature on the Charcoal Properties" *Sains Malaysiana* **50** (12), 3705-3717 (2021).
- 49) F. M. Guangul, S. A. Sulaiman, and V. R. Raghavan, "Gasification and effect of gasifying temperature on syngas quality and tar generation: A short review,"
- 50) A. Żogała, "Equilibrium Simulations of Coal Gasification – Factors Affecting Syngas Composition," *Journal of Sustainable Mining*, **13**, 30-38 (2014).
- 51) S. Suyambazhahan, "Experimental study of coconut shell fluidized bed gasification for production of fuel gas for end-use applications" *International Journal of Applied Engineering Research*, **13** (20), 14682-14688 (2018).