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Carbonization of Coconut Shell Biomass in a Downdraft Reactor: Effect of Temperature on the Charcoal Properties

(Pengkarbonan Biojisim Tempurung Kelapa dalam Reaktor Alir Turun: Kesan Suhu terhadap Sifat Arang)

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ABSTRACT

Considering the value of coconut shell biomass as renewable fuels in homes and commercial industries, its effectiveness as a biomass resource has been overlooked by our rural citizens and researchers. Carbonization experiments of coconut shell biomass were conducted in a downdraft carbonization reactor (750 mm height and 67 mm diameter) to determine the effect of temperature (250 to 600 °C, in 50 °C intervals) on the charcoal properties. This was to address the problems of traditional charcoal production methods that include; low yield, environmental pollution, unregulated temperature, and poor quality properties. Yet the scarcity of this information hampers efforts for efficient commercial production. The coconut shell biomass was obtained from a local shop in Malaysia. It was heated in the reactor at a fixed residence time of 60 min and a particle size of 5 mm with nitrogen as a carrier gas. The relationship between temperature and the properties of coconut shell charcoal has been ascertained by the findings of this analysis. The relatively high the temperature, the better the charcoal quality, but the lowest the charcoal yields, since the secondary pyrolysis reaction expends charcoal. It was noted that, up to a final temperature of 500 °C, the yield reduction was rapid; after that, it was slower at 550 °C and almost stable at 600 °C. According to the charcoal's proximate analysis, the calorific value, fixed carbon content, carbon content and ash content increased with temperature. Whereas, the charcoal density, volatile matter, moisture content, and conversion efficiencies decrease with temperature. The presence of nitrogen gas appears to have reduced combustion reactions that promote the formation of carbon dioxide (CO_2). The methods produce the least amount of air pollutants (96 g carbon monoxide (CO), 167 g CO_2, and 64 g methane (CH_4) per 1 kg of charcoal production). The type of biomass and carbonization kiln has an impact on the production of CO, CO_2, and CH_4. Thus, the carbonization reactor used in this study has the potentials to produce an eco-friendly charcoal with superior quality properties that can assist in reducing environmental pollution, by proper selections of carbonization temperature.

Keywords: Charcoal; coconut shell biomass; downdraft reactor; renewable energy; slow pyrolysis; temperature

ABSTRAK

Nilai biojisim tempurung kelapa sebagai bahan bakar yang boleh diperbaharui di rumah dan industri komersial boleh dipertimbangkan, keberkesanan bahan bakar sebagai sumber biojisim ini telah diabaikan oleh masyarakat dan para penyelidik. Kajian tentang proses pengkarbonan terhadap biojisim tempurung kelapa dilakukan dalam reaktor alir turun pengkarbonan (ketinggian 750 mm dan diameter 67 mm) untuk menentukan kesan suhu (250 hingga 600 °C, dengan selang 50 °C) pada sifat arang. Kajian ini adalah untuk mengatasi masalah penggunaan kaedah penghasilan arang secara tradisi yang meliputi: hasil rendah, pencemaran alam sekitar, suhu tidak terkawal dan sifat arang yang berkualiti rendah. Namun kekurangan maklumat ini menghalang usaha pengeluaran komersial yang cekap. Biojisim tempurung kelapa diperoleh dari sebuah kedai tempatan di Malaysia. Ia dipanaskan di reaktor pada masa mastautin selama 60 min dan ukuran zarah 5 mm dengan nitrogen sebagai gas pembawa. Hubungan antara suhu dan sifat arang tempurung kelapa telah ditentukan daripada penemuan analisis kajian ini. Secara relatif, semakin tinggi suhu semakin baik kualiti arang, tetapi arang yang dihasilkan adalah sedikit, ini kerana reaksi pirolisis sekunder mengembangkan arang. Telah diperhatikan bahawa, hingga suhu akhir 500 °C, jmlah penurunan arang adalah cepat; selepas itu, ia menjadi perlahan apabila suhu pada 550 °C dan hampir stabil pada 600 °C. Menurut analisis proksimat arang, nilai kalori, kandungan karbon tetap, kandungan karbon dan kandungan abu meningkat dengan suhu. Manakala kepadatan arang, bahan mudah meruap, kandungan kelembapan dan kecekapan penukaran menurun dengan suhu. Kehadiran gas nitrogen menunjukkan pengurangan tindak balas pembakaran yang mendorong pembentukan karbon dioksida (CO_2). Kaedah yang menghasilkan jumlah pencemaran udara paling sedikit (96 g karbon monoksida (CO), 167 g CO_2 dan 64 g metana (CH_4) setiap 1 kg penghasilan arang). Jenis biojisim dan tanur pengkarbonan memberi kesan terhadap pengeluaran CO,

CO_2 dan CH_4. Oleh itu, reaktor pengkarbonan yang digunakan dalam kajian ini berpotensi untuk menghasilkan arang mesra alam dengan sifat kualiti yang lebih tinggi serta dapat membantu mengurangkan pencemaran alam sekitar dengan pemilihan suhu pengkarbonan yang tepat.

Kata kunci: Arang; biojisim tempurung kelapa; pirolisis perlahan; reaktor alir turun; suhu; tenaga yang boleh diperbaharui

INTRODUCTION

In economic growth, energy plays a significant role. Coal, oil, and gas are the fossil fuels that take a superior part in global energy systems and account for 80% of world energy. They have negative impacts on environmental pollution and emissions of toxic gases such as CO_2, CH_4, and other greenhouse gases (Ritchie & Roser 2017). Therefore, types of energy sources, which are sustainable, are needed to gradually phase out fossil fuels, energy demand, and environmental pollution. Biomass resources possess an economically feasible and remarkable role to address future energy requirements. It is the largest renewable source of carbon on earth, which refers to any conversion process involving life, or any plant-derived material abundant on a renewable basis (Basu 2010; Yaman 2004). Biomass are gaining recognition because it can reduce environmental pollution and enhance economic and sustainable development (Ahmad et al. 2020a).

The demand for coconut products is increasing due to several benefits. This results in the generation of biomass waste from coconut industries that can be used as an energy source. The potentials of coconut shells are not well known to many researchers. As a result, the biomass is not being used to its full potential. Although it is used for making utensils, as reinforcement material in concrete mixing, automotive applications, organic fertilizer, and also as a combustion fuel by the blacksmiths and for domestic usages. Coconut shell is economical, sustainable, affordable, and abundant at a low cost. It is efficient and eco-friendly as it enhances the green environment due to several properties. Coconut shells have a high lignin content of 36% with 34% cellulose, 29% pentosan, and 1% ash that makes it suitable for charcoal production (Foraminifera 2018; Yerima 2018). Energy efficiency, reliability, flexibility, and environmental impacts are the main factors of a sustainable energy system. For a biofuel to be sustainable, it should be abundant and possesses characteristics of a good fuel with lesser negative environmental impact when compared to coal and petroleum gas (Demirbas et al. 2016). Therefore, the coconut shell is a potential raw material for charcoal production.

Charcoal has high carbon content and energy content that is comparable to high-rank coals. It is the most traded commodity in ancient times; even so, it has always been a stained and laborious process. Coconut shell charcoal has been given attention as a potential substitute for wood charcoal and coal in most countries. It serves as a domestic and industrial fuel for different applications ranging from use in medical, high quality activated carbon, renewable fuel, adsorbent, purification, and soil amendment. Charcoal productions play a part in improving the livelihood of the rural community, although it has several unfavorable environmental effects. Although there are various methods and techniques for producing charcoal, the traditional methods using earthen or metal kiln are still used by the majority of people in many countries. Local charcoal producers often place little emphasis on the quality of their charcoal product and instead focus solely on the production volume. They used a difficult and laborious traditional earth pit method to make charcoal since the nineteenth century. The process lasts for 24 days with the conventional kilns and 13 days with the improved kiln. However, the major drawbacks and limitations of these conventional biomass conversion methods include prolonged processing time, low yield, great loss of energy fraction, uncontrolled temperature, contamination with impurities, and immoderate emission of smoke. It was estimated that the production of charcoal and the use of fuelwood accounts for 1-2.4 Gt of CO_2e emissions annually (FAO 2017). For biomass fuels to compete with fossil fuels, the development of an efficient conversion technology is important (Pestaño & Jose 2016).

A sustainable conversion of biomass is carried out in a closed system with an inert environment and controlled operating factors. Slow pyrolysis involves carbonizing the feedstock biomass at a moderate temperature and residence time in an oxygen-free environment to produce charcoal as the main product along with low molecular liquids and gases (Ahmad et al. 2020a). The advantages of these include high efficiency, non-contamination of the charcoal with impurities such as sand, time management, and use of the produced liquid and gaseous biofuels. The methods regulate the process variables such as operating temperature and gas flow rate. Moreover, it does not affect the environment through the emission of toxic gases. Hence, the production of charcoal with improved technology is eco-friendlier. Various researches have been conducted to implement the use of various improved methods to produce high quality charcoal in order to solve the limitations of the conventional earth kiln and metal methods. Among these include an improved charcoal retort system using wood biomass (Chandrasekaran et al. 2019), pyrolysis reactor equipped with tar scrubbers using coconut shell biomass (Sari et al. 2020), and retort kiln using corn cob biomass (Sparrevik et al. 2015). The yield and quality of the charcoals from these kilns varies. Furthermore, no study has examined the quality and properties of charcoal produced from coconut shell using a downdraft reactor at various pyrolysis temperatures.

However, the slow pyrolysis operating factors such as temperature affects the structure and composition of the charcoal. Temperature is the main process factor that affects the thermal decomposition of biomass and solid biofuel (Basu 2010). It affects the product by lowering the calorific value that predicts the value of a fuel. Charcoal with high carbon content has high energy content. This was confirmed that the temperature affects the energy content of a product (Ahmad et al. 2020c; Basu 2010). Optimum temperature is required, when the solid product is the biofuel of interest. Exposing the biomass to higher temperatures decrease the solid yield and favor other pyrolysis products (liquid and gas) (Basu 2010). Nevertheless, the quality properties of charcoal are the basic problem that limits its diverse usage. The quality of the charcoal relies on the biomass type, the methods, and the process factors used for its processing. Therefore, to ensure charcoal has suitable qualities for many uses, a careful selection of the biomass and operating temperature is required (Dias Junior et al. 2020).

In most developing countries, charcoal usage for domestic and industrial applications is increasing exponentially. It was reported that charcoal is used for manufacturing purposes in Brazil, domestic fuel, and the food industry in Central America and sub-Saharan Africa (Chidumayo & Gumbo 2013). All the charcoal used for these applications is produced from wood trees. Therefore, an alternative to this raw material is required to ease the problem of deforestation. Due to the high demand of charcoal for barbecue, pharmaceutical, and industrial applications, charcoal with high density, energy value, fuel value index, carbon content with low ash is needed. Coconut shells contain high lignin content and its heat energy encourages the oxidation of complex carbon molecules to break up into carbon (Basu 2010). In addition, smokeless fuels are gaining popularity due to their high density, high calorific value, and low environmental impact. Coconut shell biomass possesses all this features. Hence, makes it a promising, viable alternative biomaterial for charcoal production and application in chemical industries. Nevertheless, temperature affects the quality of the charcoal. Until today, different work has been carried out to produce charcoal from biomasses using the traditional and improved kilns (Chandrasekaran et al. 2021, 2019; Sari et al. 2020) and pyrolysis reactors (Dias Junior et al. 2020). Most of the research has focused on the reactor performance, type of biomass, and other pyrolysis factors (Azargohar et al. 2014; Chen et al. 2016; Qin et al. 2020). However, each biomass has specific thermal behavior and characteristic properties. Therefore, investigating the thermal behavior of coconut shells at different temperatures is required. The scientific data on the production of charcoal from coconut shell biomass feedstock is scarce.

Therefore, investigating the effects of temperature on the charcoal properties will support charcoal production and derive coconut shell charcoal specific data. The objective of this work was to produce charcoal at different temperatures to determine relationships with the charcoal's yield, carbon yield, weight loss, carbon content, fixed carbon content, ash content, fuel value index, density, carbon conversion efficiency, and energy conversion efficiency. From these, an optimum pyrolysis temperature for maximum output and excellent quality charcoal can be revealed. Furthermore, the emissions of CO, CO_2, and CH_4 have been evaluated and compared with other methods, to investigate the potentials of the reactor settings and the biomass used.

EXPERIMENTAL

MATERIALS

The shell of Matag coconut variety was used as the feedstock sample material for the study. It was obtained from a local coconut milk shop in Seri Iskandar, Perak, Malaysia. The shells were cleaned with a knife and scraper to remove the husks. The coconut shell biomass was placed in an electric drying oven for 24 h at 105 °C. The moisture content serves as the key factor for any thermochemical conversion process and was obtained according to ASTM E871-82 standard procedure (ASTM 2013). The dried samples were crushed using a hammer and sieved by sieve analysis to obtain a size of 5 mm for the pyrolysis process. For the feedstock biomass characterizations, the shells were ground to have a fine powder of 250 μm by a grinder.

METHODS (PYROLYSIS PROCESS)

Temperature, the most influencing factor in charcoal production was selected for investigating its influence on the percentage weight loss, density, carbon content, yield, carbon yield, energy content, fuel value index, fixed carbon yield, and energy conversion efficiency. Eight temperatures were used from 250-600 °C with 50 °C increments. The residence time and particle size were kept constant at 60 min and 5 mm. These values were in the range of the slow pyrolysis process (carbonization) variables, and were selected based on the authors' previous studies (Ahmad et al. 2020c) and recommendation by Basu (2010).

A laboratory-scale downdraft reactor coupled with the liquid collection unit, and the online gas analyzer was used for the pyrolysis process as shown in Figure 1. The reactor unit was available in the Biomass Research Laboratory, at Universiti Teknologi Petronas. The reactor system was used because it has the advantages of minimizing environmental pollution that is increasingly important currently. Nitrogen gas was connected to the reactor system through a pipe and managed by a flow meter in an inert environment. 2 L/min of nitrogen was purged for 10 min before placing the feedstock into the reactor to sweep away any volatile vapours. The advantage of purging the inert gas is to avoid thermal oxidation of the feedstock which may assist in the generation of CO_2, CO, NO_2, and SO_2 gases. Once the set temperature was achieved through the temperature controller, 100 g of the coconut shells sample was weighed, fed, and heated for 60 min for the process to occur. Upon heating the biomass, the breakdown of the organic content of the coconut shell goes through a thermal cracking reaction and condensation reaction. At the early stage of carbonization, water evaporates as white fumes from the reactor and settled at the condenser as a mixture of water, condensable and combustible gases. Thus, the carbonization process occurs in two stages via drying and pyrolysis. The condensable gases settled in the condenser, and the gaseous products (H_2, CH_4, CO, and CO_2) pass through a pipe to the online gas analyzer for analysis. The charcoal was collected and put in a desiccator for further analysis. The procedure was repeated three times for each temperature.

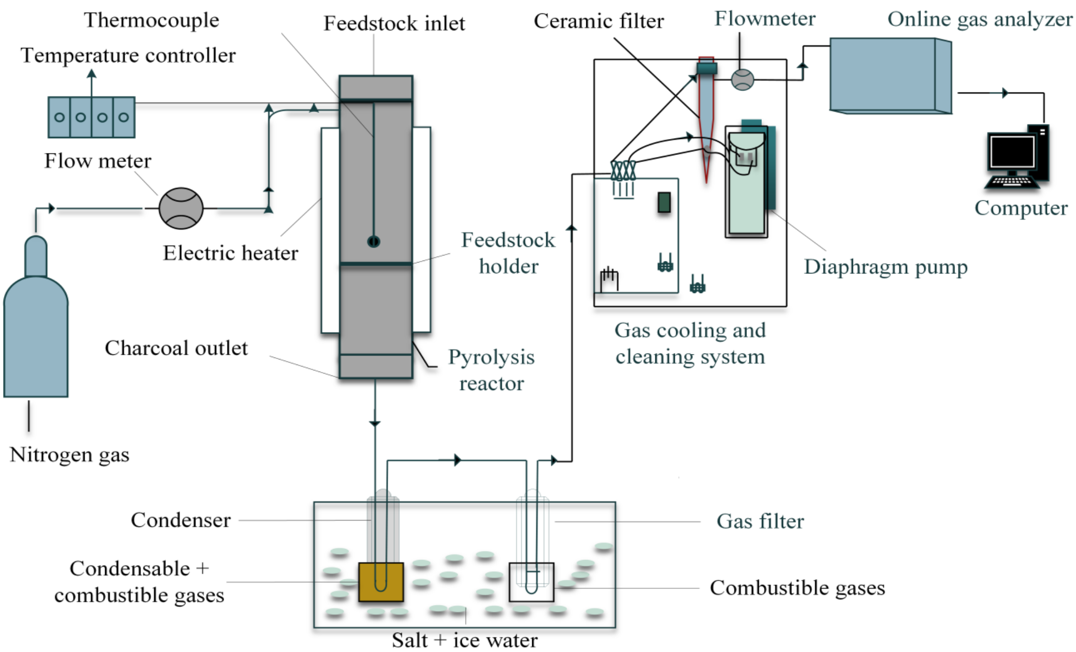

FIGURE. 1 Experimental setup for coconut shell charcoal production

BIOMASS AND CHARCOAL CHARACTERIZATION

The coconut shell biomass and charcoal were characterized by analytical examination to investigate the properties and potentials of the sample as a fuel material concerning environmental sustainability. The proximate test shows the strong relationship of some characteristic's potential of a sample for energy production. It was carried out with a thermogravimetric analyzer using ASTM E1131-08 (ASTM 2014) for evaluating the moisture, ash, volatile matter, and fixed carbon of the sample. The carbon content was measured using ASTM D3176-09 (ASTM 2015) standard procedure with the CHNS-932 analyzer because charcoal consists of carbon. The calorific value was obtained according to the ASTM D4809-18 standard procedure (ASTM 2018) using an IKA C-6000 isoperibol bomb calorimeter. It is an important parameter for thermochemical conversion processes that determines the samples' energy content. The fuel value index (FVI) is a key factor that determines the suitability of fuel material. It was obtained according to Bhatt and Todaria (1992) equation using the values of ash, moisture, density, and energy content of the sample as shown in (1).

$$FVI = (CV \times D) / A) \quad (1)$$

where FVI is the fuel value index; CV (MJ/kg), D (kg/m^3), and A (%) are the charcoal's calorific, density, and ash content, respectively. The density was calculated as mass divided by the volume displaced by the charcoal.

The charcoal yield is the yield of the recovered coconut shell charcoal obtained after the pyrolysis process calculated from (2). It was determined based on the weight percentages of the dry ash-free charcoal according to Ronsse et al. (2013). The method avoids positive bias in calculating the charcoal yield in case the sample has a high amount of mineral ash content.

$$Charcoal\ yield = \frac{(M_c - M_{ash.c})}{(M_b - M_{ash.b})} \times 100\% \quad (2)$$

where M_c represents the charcoal's weight (g); M_b represents biomass feedstock's weight, $M_{ash.c}$ and $M_{ash.b}$ represents the ash content (g) of the charcoal product and biomass feedstock.

The carbon yield was expressed in terms of the charcoals and biomass feedstock's carbon content using (3).

$$C_{Yield} = Y_{Charcoal} \times \frac{C_{Charcoal}}{C_{Biomass}} \quad (3)$$

where C_{yield} represents the carbon yield; $Y_{Charcoal}$ represents the yield of the coconut shell charcoal, $C_{Charcoal}$ and $C_{Biomass}$ represents the charcoal and biomass feedstock carbon content (%).

The fixed carbon yield (FCY) or carbon conversion efficiency was calculated as (4):

$$FCY = \left[Charcoal\ yield \times \left(\frac{Fixed\ carbon\ content\ of\ charcoal}{100 - ASH_{biomass\ feedstock}}\right)\right] \quad (4)$$

The energy conversion efficiency was calculated using (5).

$$n_{Energy} = Y_{Charcoal} \times \frac{CV_{Charcoal}}{CV_{Biomass}} \quad (5)$$

where n_{Energy} represents the energy conversion efficiency; $Y_{Charcoal}$ represents the yield of the coconut shell charcoal (%); and $CV_{Charcoal}$ and $CV_{Biomass}$ are the calorific values of the charcoal and coconut shell biomass all in MJ/kg, respectively.

EMISSIONS OF GREENHOUSE GASES MEASUREMENT

The amount of the gases generated at the maximum temperature (600 °C) was measured in volumetric percentage using an online gas analyzer as described in the methods (pyrolysis process) above. The pollutants measured during the carbonization process of the coconut shell biomass were CO, CO_2, and CH_4. They were expressed in grams per yield of charcoal produced.

RESULTS AND DISCUSSION

Coconut shell charcoal is used as a feedstock for the manufacturing of chemicals, in purification and other industries, such as medicines and cosmetics. Therefore, to harness the biomass potentials for the carbonization process to produce such charcoal for this application, physical and chemical analysis of the biomass is first required. To estimate the efficiency of the reactor used and the methods of obtaining high-grade charcoal, the study evaluates the process based on the temperature profile.

CHARACTERIZATION TESTS OF COCONUT SHELL BIOMASS

Thermogravimetric analysis is the easiest method for evaluating the pyrolysis behavior of fuel. The results of the physicochemical properties of the coconut shell biomass via the content of moisture, fixed carbon, ash, and volatile matter are summarized in Table 1. These properties are essential before thermochemical conversion of any biomass (Ahmad et al. 2017). From the results, a moisture content (MC) of 5.80%, volatile matter content (VM) of 71.58%, ash content (AC) of 1.20%, and fixed carbon (FC) of 21.40% were obtained. With the high volatile matter, excellent yields are expected from coconut shells through slow, fast, and flash pyrolysis for liquids and gaseous products. High volatile matter in given biomass indicates the presence of light hydrocarbons, hydrogen, CO_2, and CO (Zainab et al. 2015). The biomass has a low ash value. The presence of high ash content in biomass leads to inferior reactions in a thermochemical process, hence low efficiency (Zainab et al. 2015). Therefore, the biomass does not require pre-treatment for removal of ash cations before any thermochemical conversion. Moreover, coconut shells having high fixed carbon and low moisture content are recommended for charcoal production from slow pyrolysis (Ahmad et al. 2020a).

The coconut shell biomass has 40.0% carbon content (CC), 5.25% hydrogen content (HC), 0.18% nitrogen content (NC), 0.14% sulfur content (SC), and 54.39% oxygen content (OC) from the ultimate analysis. The biomass has a considerable amount of these elements. The carbon content is high which may increase the heating value. It also has a lesser amount of nitrogen and sulfur content which will aid the production of toxic and undesirable combustion by-products such as oxides of nitrogen (NOx) and sulfur (SO_X). According to the European Commission (2008), the nitrogen content of the fuel is responsible for nitrous oxide formation emissions, which are one of the most significant environmental impacts of solid biofuel combustion (Yerima 2018). The coconut shells have nitrogen content in low amount. The higher calorific value of fuel talks more about the energy that will be released during the process of ignition. The standard range of biomass calorific value is 15 to 20 MJ/kg, which is near the value of low-rank coal (Basu 2010). The energy content of the coconut shell feedstock material is found to be high (20.30 MJ/kg). Thus, confirming coconut shells' potentials through thermochemical technology as an energy source for power generation.

TABLE 1. Characterization of coconut shell for thermochemical process

Biomass Material	Proximate Test				Ultimate Test					CV (MJ/kg)
	MC (%)	VM (%)	AC (%)	FC (%)	CC (%)	HC (%)	NC (%)	SC (%)	OC (%)	
Coconut shell	5.80	71.58	1.20	21.40	40.00	5.25	0.18	0.14	54.39	20.30

*(OC = 100 – CC – HC– NC – SC)

PROXIMATE ANALYSIS OF COCONUT SHELL CHARCOAL

Carbonization or slow pyrolysis is generally performed to enhance the properties of carbonized products. As a result, it is important to discuss the influence of the pyrolysis temperature on the properties of the charcoal, as it has a direct impact on the charcoal's quantitative characteristics. Table 2 presents the values of the charcoal's weight, fixed carbon, ash, carbon, and density in the temperature range (250 to 600 °C). This was to understand the variation of these properties concerning temperature difference. After carbonizing the coconut shell biomass, a black shining carbon material was obtained (coconut shell charcoal). The weight of the produced charcoal was found to range from 25.5 ± 0.1 to 53.1 ± 0.08 g at a temperature range of (600 to 250 °C). It was found that the weight of the charcoal was higher at lower temperatures. This could be due to the partial carbonization of the biomass that results in the removal of water and some volatile materials. The moisture content decreases from 1.38 to 1.07% with the carbonization temperature. High temperatures cause the volatiles to devolatilize and form more solids, resulting in the sudden change in moisture content at 450 °C. Similar findings were reported by Ahmad et al. (2020a) and on coconut shell charcoal. However, Baygan et al. (2019) observed a fluctuating results on the coconut shell charcoal moisture content with temperature. At a temperature of 350 °C, the moisture content was 5.65 and 2.73% at 400 °C. The moisture content suddenly increases at 450 °C and reach maximum (10.6%) at 550 °C. However, it later decreased to 2.22% at 600 °C (Baygan et al. 2019). The ash content of the recovered charcoal ranged from 1.01 to 1.19%. All the ash content did not exceed the standard value. Ash content of 0.50 to 5% is acceptable for excellent quality charcoal (FAO 1987). The ash content of this studies were lower than those obtained by Sari et al. (2020), 2.26 and 1.36% of coconut shell charcoal at 500 °C with conventional and improved kiln. The volatile matter decreased from 17.6 to 12.9%, while the fixed carbon content increases from 57 to 86.65% with temperature, respectively. The increase of fixed carbon was due to the thermal decomposition and escape of volatiles at higher temperatures. A similar trend of decrease in volatile matter and increase in fixed carbon content of charcoal with temperature was observed by other studies (Baygan et al. 2019; Yang et al. 2016). However, the fixed carbon content and volatile matter at 250 °C were better than those obtained by Baygan et al (2019) at the lowest temperature 350 °C. This could be due to the residence time, feedstock particle size and type of reactor. Therefore, elevated temperatures support the formation of fixed carbon. Charcoal with fixed carbon content from 50 to 95% is referred to as excellent quality charcoal (FAO 1987). Activated carbon is produced from a material with a low amount of ash and a high amount of fixed carbon (Azargohar et al. 2014). Charcoal may be best suited for grilling and barbecue if it has a fixed carbon content higher than 75% and an ash content below 8%, according to European standards (1860-2:2005 2004).

As the biomass is heated, the generation of carbon continues. The carbon content increased with temperature from 59.7 to 85.6%. The carbon content is higher at elevated temperatures because higher temperatures result in carbon formation. Increasing the temperature causes the removal of volatile matter, thus, the formation of high carbon content. This is due to the heat energy that causes the volatiles to escape (Sari et al. 2020). This supports the findings of the increased carbon content at elevated temperatures. It was noticed that charcoals with a high amount of carbon content have good combustion properties and energy content. The carbon content (87%) of the current study is higher than those of coconut shell charcoal (81%) by Sari et al. (2020). There exists an inverse relationship between the charcoal density and the pyrolysis temperature. The density of the coconut shell charcoal decreases with temperature between 3300 and 769 kg/m^3. This could be due to the increase in the charcoal volume. Related results were reported by FAO (1962).

TABLE 2. Physical properties and proximate analysis of charcoal produced at different carbonization temperature

Temperature (°C)	Mass of charcoal (g)	MC (%)	AC (%)	VC (%)	FCC (%)	CC (%)	Density (kg m^{-3})
250	53.1 ± 0.08	1.38	1.01	17.6	57	59.7	3300
300	42.3 ± 0.07	1.32	1.03	17.3	70	67.6	2146
350	38.5 ± 0.05	1.29	1.04	16.2	75.3	70.4	1269
400	34.1 ± 0.1	1.28	1.04	15.7	79.2	74.6	1157
450	30.8 ± 0.06	1.25	1.06	14.9	82.7	77.8	1038
500	28.6 ± 0.08	1.13	1.08	13.7	84.3	82.3	923
550	26.4 ± 0.13	1.1	1.12	13.0	85.2	83.9	857
600	25.5 ± 0.12	1.07	1.19	12.9	86.7	85.6	769

A non-uniform color was observed at 250 and 300 °C due to incomplete carbonization of the biomass. The charcoal obtained at a temperature of 350-600 °C, are light and fragile with a darker color. The size of the charcoal (diameter, length, and thickness) was also affected by the temperatures. These cause their density to decrease with temperature. In terms of transportation and handling, these charcoals may suffer and shatter due to their lower density. Therefore, proper packaging is required.

THE INFLUENCE OF TEMPERATURE ON THE CHARCOAL WEIGHT LOSS

The percentage of weight loss can be used to explain the thermal degradation of the coconut shell at different temperatures. The results in the percentage mass loss of the charcoal at different temperatures have been presented in Figure 2. The percentage of weight loss was ranged from 46.8 to 74% at 250 to 600 °C temperatures. The percentages of mass losses of the recovered charcoal were progressing with temperatures. The maximum temperature (600 °C) gave the highest percentage weight loss (74%), and the lowest (250 °C) have the lowest (46.8%). Lignocellulosic organic components are the main basic unit of biomass. The difference in their structural framework makes them behave in diverse ways during thermochemical conversion, such as pyrolysis (Strezov et al. 2017). Hemicellulose and cellulose occur above 180 to 400 °C, with lignin decomposition starts from 280 to 500 °C. The mass loss at elevated temperatures can therefore, be assigned to the thermal degradation of lignin. This is obvious because the decomposition of the biomass feedstock at lower temperatures was not completed at lower temperatures. The color of the solid does not change to grey-black color completely and was hard to crush. Hence, low volatile matter removal with high solid residue. Consequently, the remaining volatile matter in the charcoal escapes at elevated temperatures, which results in a high percentage of weight loss. A similar trend of weight loss was observed by Ahmad et al. (2020a).

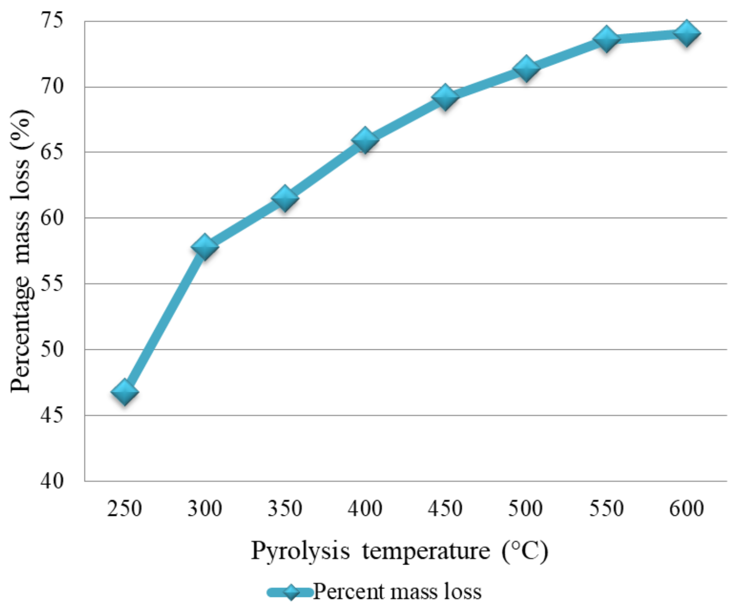

FIGURE 2. The influence of the pyrolysis temperature against the percentage weight loss of the resulting coconut shell charcoals

THE IMPACT OF TEMPERATURE ON THE YIELDS

The values of the charcoal yield decrease from 52.9 to 25.1% with temperature as illustrated in Figure 3. At elevated temperatures, the yields of the charcoal are lower. The volatile materials with a low boiling point were emitted at increasing the heat, thus causes the sudden charcoal yield to decrease from 52.9 to 41.9% in the temperature range 250-300 °C. Consequently, as the temperature was increased above 400 °C, rapid volatile evolution was promoted, hence the yield decreases up to 25.6% at 550 °C. From 550 to 600 °C, the decrease in yield is only 0.5%. This indicates the biomass has reached the carbonization stage, and mass loss after 550 °C is negligible. Further increase in temperature might affect the quality of the charcoal. At higher temperatures, the degradation of the feedstock biomass molecules and the release of volatile components is so quick (Yang et al. 2020), hence, fewer charcoal yields. A similar trend has been reported on coconut shell charcoal, apple branch biochar and several kinds of biochar's (Ahmad et al. 2020b, 2020c; Dias Junior et al. 2020; Yang et al. 2020; Zhao et al. 2018). Nevertheless, Baygan et al. (2019) reported a different trend with variation among the charcoal yield with temperature (350 to 600 °C). Maximum yield (39%) was obtained at a temperature of 500 °C. At 500 °C, Sari et al. (2020) obtained a charcoal yield of 23% with conventional kiln and 28% with improved kiln equipped with tar scrubber. The difference among the charcoal yield could be attributed to other pyrolysis factors such as residence time, heating rate, reactor type, biomass type, and feedstock particle size.

A decrease in the charcoal yield due to the rapid increase of the carbonization temperature causes carbon yield to drop (Figure 3). The values of the carbon yield at increasing temperature (250-600 °C) were decreased from 78.8 to 53.6%. The carbon yield depends on the charcoal yield and carbon content. A slight decrease of 0.05% is observed from 550 to 600 °C on the charcoal carbon yield. The charcoal at lower temperatures could be corrosive and with low-quality properties (Ahmad et al. 2020b).

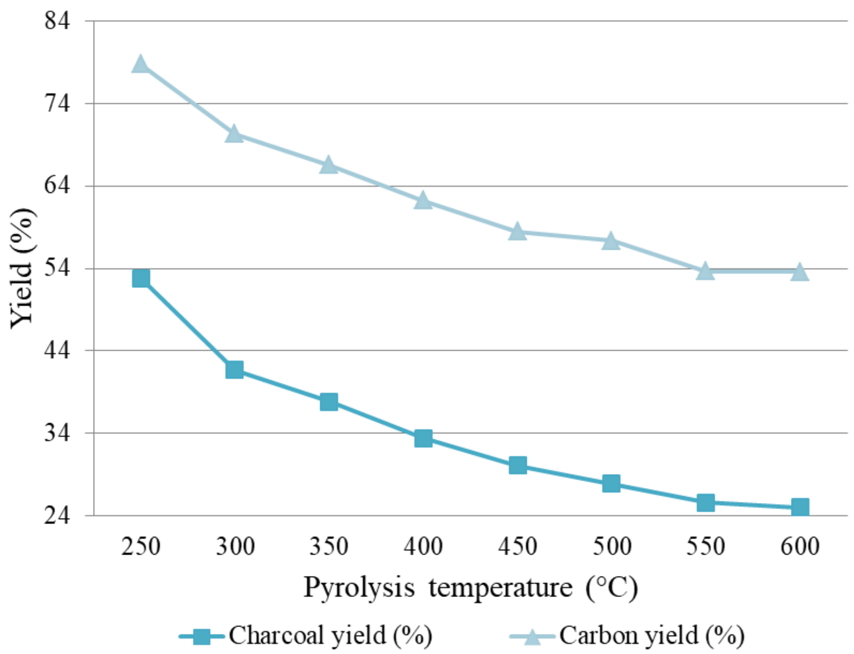

FIGURE 3. The influence of the pyrolysis temperature against the yield and carbon yield

THE IMPACT OF TEMPERATURE ON THE CHARCOAL'S ENERGY

As low temperature produces high charcoal yield, the quality of the charcoal as a fuel is of paramount importance. To achieve best charcoal with the required energy content to serve as a fuel, the relationship between the operating temperature and the energy content is crucial. A higher calorific value was obtained at higher temperatures and the fuel value index oppositely as shown in Figure 4. The variation of the energy content among the charcoal samples is dependent on the temperature variation. The calorific value ranges between 25 ± 0.13 and 36.7 ± 0.06 MJ/kg. The calorific value increased with temperature, and reached a maximum value between 550 and 600 °C, (35.3 and 36.7 MJ/kg), respectively. The proportion of some quality factors is attributed to the amount of calorific value. The amount of moisture content in a charcoal affects its heating value. The higher the moisture content, the lower the calorific value. The moisture content is higher at low temperatures, hence the low amount of calorific value at these temperatures. In order to produce a charcoal with high calorific values, and easy-to-ignite, the moisture content should be low (Sari et al. 2020). The calorific values of this study are higher than the calorific value of coal (16.16 MJ/kg) (Song et al. 2016), coconut shell charcoal (34 MJ/kg) (Sari et al. 2020), and charcoal from different biomass (coconut shell (17.5 MJ/kg), palmyra shells (12.8 MJ/kg), and doum shells (11.1 MJ/kg) (Kongnine et al. 2020). The results of this study were similar with those in the literature on coconut shell charcoal (Ahmad et al. 2020b, 2020c). Hence, the calorific value of a charcoal depends on the temperature and other pyrolysis factors.

The fuel value index is another factor used to determine the suitability of fuel material (Figure 4). The fuel value index of the charcoal was found to decrease from 81691 to 23743 with temperature. This could be because at elevated temperatures, the density and ash content of

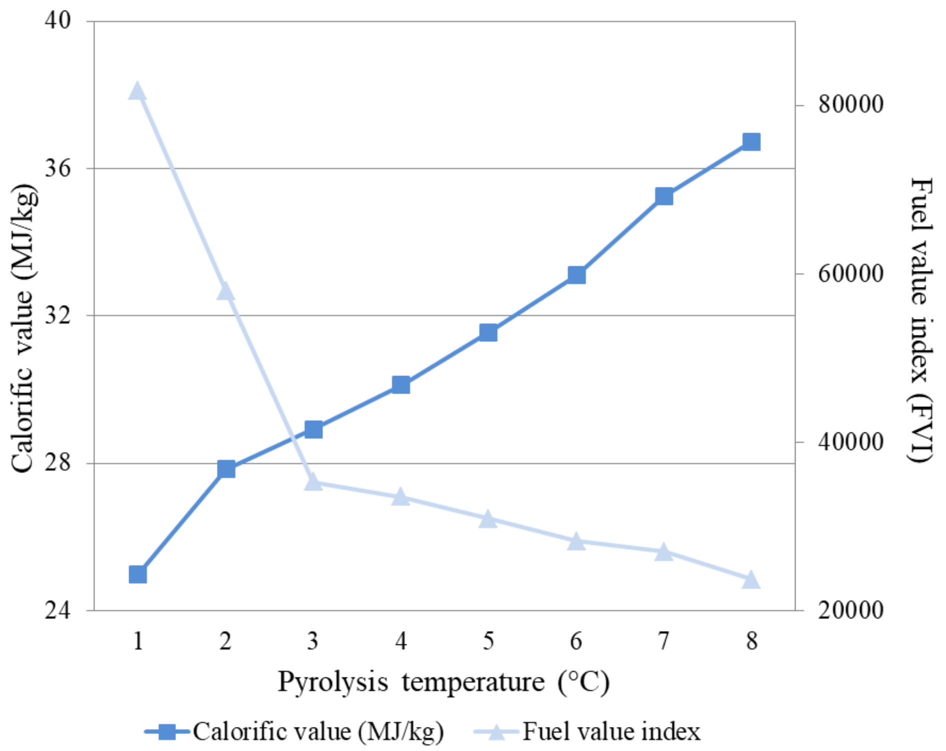

FIGURE 4. The effect of the pyrolysis temperature on the calorific value and fuel value index

the charcoal are less, consequently producing a lower fuel value index. The fuel value index shows that the charcoal with a high energy value at the lower temperatures can be used as a domestic fuel material.

THE IMPACT OF TEMPERATURE ON CONVERSION EFFICIENCIES

Figure 5 illustrates the relationship between the temperature, carbon conversion efficiency, and energy conversion efficiency of the coconut shell charcoal at 250 to 600 °C temperature range. The yield and the fixed carbon of the charcoal cannot portray the efficiency of the system; hence the carbon conversion efficiency further explains. Carbon conversion efficiency shows the total chemical changes a product undergoes during thermochemical conversion (Antal et al. 2000). The temperature has a significant effect on the carbon conversion efficiency. It was found to decrease continually with the risen temperature (250-600 °C) from 30.5 to 22%. At a temperature between 550 and 600 °C, only 0.1% decrease was observed. Enhancement of secondary reactions that causes an increase in vapor at elevated temperatures lowers the carbon conversion efficiency (Chandrasekaran et al. 2019).

The energy conversion efficiency of the charcoal at the lowest and highest temperatures was calculated based on the charcoal yield, and the calorific value of the charcoal and biomass. The charcoal efficiency is calculated to be 61.5% at the lowest temperature, and 42.3% at the highest temperature. The energy yield depends on the amount of the calorific value and the charcoal yield. The energy conversion efficiency of the charcoal was highest at the minimum temperature. At elevated factors, the mass loss is high, consequently, low yield, thus, the energy conversion efficiency is low.

MEASUREMENT OF GASES FROM THE DOWNDRAFT REACTOR AND COMPARISON WITH OTHER CHARCOAL KILNS

A high amount of white fumes is produced during carbonization, more especially when using the traditional methods. The air pollutants are CO, CO_2, CH_4, NO_X, and SO_X that may have a long-term effect when inhaled consecutively. The emission of gases (CO, CO_2, and CH_4)

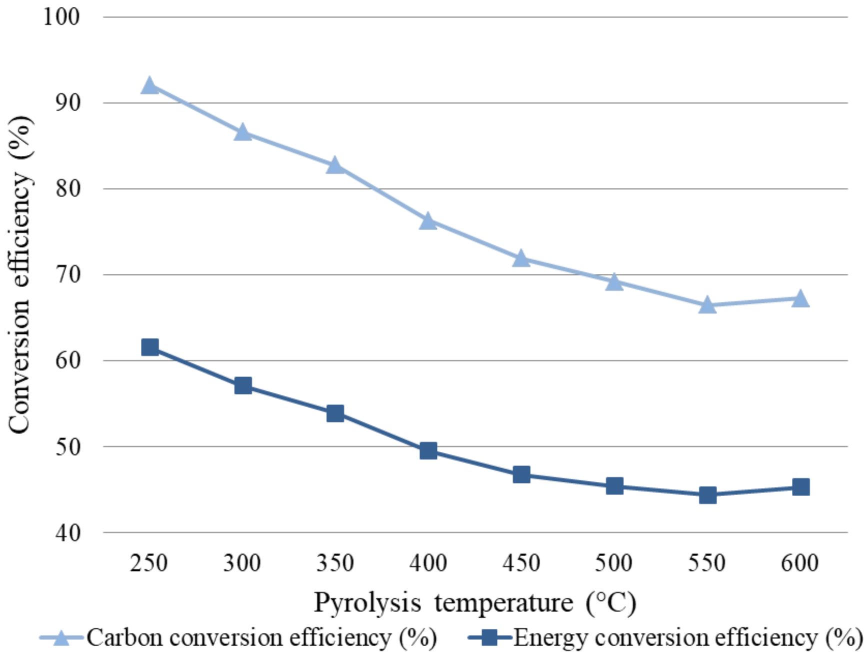

FIGURE 5. The impact of the pyrolysis temperature against the carbon conversion efficiency and energy conversion efficiency

from the downdraft rector was compared with other kiln reactors to evaluate the environmental influence and reliability of the reactor as shown in Table 3. The presented emission for this study was recorded at the highest temperature of 600 °C. During the slow pyrolysis process, lower molecular gases were produced that condense in a condenser as liquids. The combustible gases pass through the gas cleaning unit to the online gas analyser. No gases were released into the atmosphere. The mean values of the gases per 1 kg of charcoal obtained during the carbonization of the coconut shell to charcoal were 96.4 g of CO, 1666.9 g of CO_2, and 64.3 g of CH_4. Except for the methane composition, those values obtained were much lower than those from other studies. The values of the gases produced per 1 kg of charcoal are shown in Table 3. It was found that, for 1 kg of charcoal; 215 g of CO, 1985 g of CO_2, and 44 g of CH_4 were produced with retort kiln (Sparrevik et al. 2015). Similarly, 135 g of CO, 2646 g of CO_2, and 32.5 g of CH_4 with improved natural carbonizer (Chandrasekaran et al. 2019). The results of the gases with earth kilns are higher from both the reference. They include 583 g of CO, 3682 g of CO_2, and 54.9 g of CH_4 (Sparrevik et al. 2015), and 376 g of CO, 3454 g of CO_2, and 44.8 g of CH_4 (Chandrasekaran et al. 2019). This shows that the type of method used in terms of the kiln, greatly affects the generation of the greenhouse gases. The downdraft reactor used in this study has shown lower emission of these gases compared to conventional kiln using coconut shell as the feedstock biomass material.

Apart from the type of method used for charcoal production, the type of biomass feedstock also dictates the amount of air pollutant gases to be generated. As such, coconut shell is a reliable source of biomass material to produce charcoal in a downdraft reactor. Therefore, from the observed data, the methods, reactor type, and biomass type are a key factor that contributes to the release of greenhouse gases to the atmosphere during the carbonization process of biomass. Thus, these factors should be taken into consideration before any charcoal production. The methods used in this study are good to produce methane for heat and electricity.

TABLE 3. Comparison and emissions of greenhouse gases per 1 kg of charcoal

Type of reactor	Type of biomass	Pollutants emission in g per kg of charcoal			
		CO	CO_2	CH_4	References
Laboratory-scale downdraft	Coconut shell	96.4	166.9	64.3	Current study
Earth brick kiln	Corn cob	583	3682	54.9	Sparrevik et al. (2015)
Retort kiln	Corn cob	215	1985	44.0	Sparrevik et al. (2015)
Improved kiln	Wood	135	2646	32.5	Chandrasekaran et al. (2019)
Earth kiln	Wood	376	3454	44.8	Chandrasekaran et al. (2019)

Conclusion

Charcoal production with a downdraft reactor and regulated pyrolysis factors is an eco-friendly process. Coconut shell biomass has the potential to replace the use of coal and wood for charcoal production. Investigating the pyrolysis factors on the charcoal properties can contribute significantly to environmental sustainability. Coconut shells were carbonized in a downdraft reactor to evaluate the impact of temperature on the charcoal properties. Elevated temperatures decrease the amount of charcoal yield, density, carbon yield, fuel value index, energy, and carbon conversion efficiency. The ash content, carbon content, fixed carbon content, and energy value, increase with high temperatures. The highest temperature (600 °C) produces the lowest charcoal yield (25.1%) and the highest energy content (36.7 MJ/kg). The carbon yield and carbon conversion efficiency of 62 and 30% were highest at the lowest temperature (300 °C). The charcoal produced from coconut shell at a temperature above 450 °C has a noteworthy effect on the yield. Therefore, selection of a reactor system, temperature and other process factors is a key factor in charcoal production. These will establish optimum conditions for charcoal production to improve the charcoal yield with standard quality properties, and reduce air pollution.

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