Pretreatment of Coconut Shell by Torrefaction for Pyrolysis Conversion

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Abstract. This study describes the influence of torrefied coconut shell (CS) as solid fuel on pyrolysis product yield. The CS were torrefied and then pyrolysed in a fixed-bed reactor at different temperature and reaction time. The raw and torrefied CS were analysed for mass and energy yield, proximate analysis and ultimate analysis. The pyrolysis products yield were compared between raw CS and torrefied CS. The results showed that the properties of torrefied CS in terms of proximate and ultimate analysis were enhanced than raw CS. The calorific value for torrefied CS increased 17.17 MJ/kg to 22.25 MJ/kg. The optimum condition obtained for torrefaction pretreatment was at 275 °C and reaction time of 60 min. The highest bio-oil yield of 45 % from pyrolysis process was at temperature and reaction time of 500 °C and 6 min, respectively. Thus, these results indicate torrefied CS was a suitable fuel feedstock to conduct in thermal conversion such as pyrolysis.

1. Introduction

With the growing global population and industrialisation, energy consumption is continually increasing. Biomass is a renewable resource that has many attention recently due to environmental concerns and rising energy demand. Biomass is rapidly becoming a significant contribution to the energy mix, as it is both carbon-neutral and sustainably produced. However, using fuels made from raw biomass has serious consequences during biomass thermal conversion. Raw biomass has relatively low energy, high moisture and oxygenated compound, hygroscopic behavior and poor grindability [1,2]. Accordingly, the pretreated or torrefied biomass which has been improved in energy density, hydrophobicity and grindability overcome the weakness of untreated biomass, then driven to be applied in thermochemical conversion [3,4]. As a result, there has been a surge in interest in identifying and developing biomass pretreatment methods. The thermal pretreatment or torrefaction work at low temperature between 200 - 300 °C which operated in the absent of oxygen, upgraded the raw feedstock to more value feedstock. The torrefied biomass has high calorific value and carbon fraction with low moisture content and O/C ratio compared to the original material. The energy value
of torrefied material will increase with increasing the carbon content and calorific value [5]. As pretreatment conditions became more severe between temperature of 250 to 300 °C, this led to more qualified and energy-dense solid fuel with higher fixed carbon content, increased calorific values and reduced hydrogen and oxygen contents [6]. Thus, this study aims to discover the properties of torrefied coconut shell and product yield of torrefied coconut shell during pyrolysis. This study enhanced the new knowlegde in pretreatment prior to thermal conversion where torrefaction was conducted before pyrolysis in order to produce better characteristics of solid fuel and bio-oil [7,8].

2. Procurement selection criteria in the cost control perception

2.1. Materials
Coconut shell (CS) was employed as a biomass sample. CS was obtained from the market in Kangar, Perlis. CS was sun-dried for four days before being ground and sieved to obtain particle sizes ranging from 425 to 600 μm.

2.2. Proximate and Ultimate Analysis
The properties of raw CS and torrefied CS were studied using proximate and ultimate analyses. To conduct proximate analysis, ASTM D121 was utilised as a reference, which included moisture, fixed carbon, ash and volatile matter content. In terms of the ultimate analysis, an elemental analyzer was employed to examine elements like carbon (C), hydrogen (H), oxygen (O), nitrogen (N) and sulphur (S).

2.3. Torrefaction
At an atmospheric pressure, torrefaction is carried out in a vertical fixed-bed reactor with an internal diameter of 60 mm and a height of 300 mm, as shown in Figure 1. The reactor is heated by an electric furnace, which is located adjacent to the reactor. In the crucible, 5 g of CS were weighed and placed in the reactor’s centre. Before starting the experiment, a nitrogen gas flow rate of 0.5 L/min was flushed into the reactor to provide an inert atmosphere. The experiment was carried out at a heating rate of 20 °C/min and a torrefaction temperature range of 200 °C - 300 °C. The torrefaction has been conducted with a constant nitrogen flow rate and a variable holding time parameter.

Figure 1. Schematic diagram of vertical fixed bed reactor.

The mass yield, calorific value, energy density and energy yield was calculated using equation (1) to equation (4) [9].
Mass yield, wt. % = \[
\frac{\text{Mass of torrefied product}}{\text{Mass of raw material}} \times 100 \%
\] (1)

Calorific value (CV), \[
\text{CV} = \frac{0.3383C + 1.422 \times H - O}{8}
\] (2)

Energy density = \[
\frac{\text{CV of torrefied product}}{\text{CV of raw material}}
\] (3)

Energy yield, % = \[
\frac{\text{Mass yield}}{\text{Energy density}}
\] (4)

2.4. Pyrolysis
This experiment was carried out in a vertical fixed bed reactor. Pyrolysis temperatures were 400, 450, 500 and 550 °C, with holding time of 2, 4, 6, 8 and 10 min. 5 g of torrefied CS was inserted in the reactor tube. The nitrogen flow rate set to 0.5 L/min to create inert atmosphere in the reactor. The heating rate for pyrolysis is maintained at 80 °C/min. The product yield of bio-char and bio-oil was weighted, while the bio-gas was calculated by different of the total product.

3. Results and discussion
3.1. Proximate and ultimate analysis
The proximate and ultimate analysis for both raw and torrefied coconut shell are shown in Table 1. Raw CS has high moisture content of 5.67 %, reduced to 2.53 % during torrefaction. The cell wall polymers containing hydroxyl (-OH) groups in raw biomass are able to absorb moisture into the walls and water capacity is hold through bonds of hydrogen [10]. The volatile content also decrease slightly after torrefaction from 73.89 % to 71.67 %. Due to volatilisation, volatile matter decreased after thermal pretreatment [9]. Fixed carbon content rises up more than 20 % as temperature increased to 275 °C. Continuous reactions of decomposition occurred at higher temperature which cause reduction of volatile content and increased of fixed carbon content [5]. Ash content experienced insignificant increase to 0.94 %. Due to the catalytic effect of ash, raw biomass materials with a low level of ash is suitable for producing pyrolysis oil [4].

| Analysis                  | Raw CS   | Torrefied CS |
|---------------------------|----------|--------------|
| Proximate analysis        |          |              |
| Moisture, %               | 5.67     | 2.53         |
| Volatile matter, %        | 73.89    | 71.67        |
| Fixed carbon, %           | 19.55    | 24.86        |
| Ash, %                    | 8.89     | 0.94         |
| Calorific value, MJ/kg    | 17.17    | 21.86        |
| Ultimate analysis         |          |              |
| Carbon, %                 | 48.35    | 61.84        |
| Hydrogen, %               | 6.21     | 4.98         |
| Nitrogen, %               | 0.18     | 0.41         |
| Sulfur, %                 | 0.01     | 0.01         |
| Oxygen*, %                | 45.25    | 33.46        |

*by different
3.2. Mass yield, energy yield and energy density of torrefied CS

Figure 2 shows the mass yield of torrefied CS under different torrefaction temperature. From the figure, the mass yield of the char declined when the temperature of torrefaction increased. The solid yield of torrefied CS ranges from 90 % to 82 %, 92 % to 86 %, and 92 % to 77 % for 30 minutes, 60 minutes and 90 minutes, respectively. High mass yield is obtained at temperature of 200 °C which is around 92 %. [7] reported that solid yield reduced due to loss of water content as the temperature rises. This also mean that there is low degradation of organic content at this temperature and moisture content is reduced after torrefaction. Due to large amount of hemicellulose degradation, solid yield decreased as the temperature and residence time rises [11]. At time 30, 60 and 90 minutes, respectively the solid conversion rises from 10 % to 18 %, 8 % to 14 % and 8 % to 23 %. At time 90 minutes and higher temperature, the solid conversion is more than 10 % compared to at time 30 minutes and lower temperature which is only 8 %. Solid conversion increased when the sample were heated from 200 °C to 300 °C along with a longer holding time. Mass yield decreases because of losing constituent component of CS and volatile matter in combustible gas form released [12].

Energy yield is an important indicator of the energy amount maintained after pretreatment. Figure 3 shows the energy yield of torrefied CS. The energy yield decrease clearly but increase as the feedstock was increased from 5 g to 6 g at temperature 250 °C until 300 °C. The energy yield for torrefied CS was drastically shot up to 111.43 % at temperature 250 °C. [13] reported that biomass feed rate will affect the energy yield where energy yield decreased at beginning but increases as feed was added to a given temperature.
Energy density of torrefied CS is demonstrated in Figure 4 which shows growth trend at various torrefaction temperature. Energy density shows a big increase after temperature at 225 °C. This prove as temperature increased along with the time the calorific value also increased as the energy density shows this trend. The energy density of raw biomass is increased by torrefaction, which enhances the fuel characteristics [14]. The energy density was similar beyond the temperature of 250 °C showed that the optimum condition has been attained [9].
3.3. Product yield of pyrolysis

Figure 5 shows the influences of temperature to product yield from pyrolysis of torrefied CS. Char clearly decreased as temperature increased. Both gas and liquid yield increased as the temperature increased. However, liquid yield reach optimum condition at 500 °C and any higher temperature causes yield to decline. The highest bio-oil yield was 25 % at temperature of 500 °C and holding time of 6 minute. Due to secondary reactions of bio-oil, the condition favored to yield more gas and char above temperature of 500 °C [15]. Therefore, the temperature is a significant parameter for pyrolysis product yield. In order to maximize bio-oil, a high heating rate must be used along with temperature ranges 450-600 °C and short reaction time [16], [17].

![Figure 5. Effect of temperature on product yields from pyrolysis of torrefied coconut shell.](image)

4. Conclusion

The properties of coconut shell were improved both physically and chemically after torrefaction. The moisture and volatile matter content decreased and the fixed carbon increased for torrefied coconut shell. The optimum torrefaction condition was determined at torrefaction temperature of 275 °C and reaction time of 60 min. This indicate torrefied CS is a suitable fuel feedstock to conduct thermal conversion. As for pyrolysis, the product yield was successfully evaluated after torrefaction. The char yield decreased, liquid yield increased, and gas yield increased with rising pyrolysis temperature. Therefore, torrefaction pretreatment is recommended before undergo thermal conversion to enhance the fuel quality.

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