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The Effect of Varying Torrefaction Temperature on the Physical and Mechanical Properties of Briquettes Made from King Grass

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Abstract

Indonesia is a country which has rich biological diversity. King grass (Pennisetum Purpupoides) is one of biological species which easily grow but has not yet been optimally used. This study examined the physical, mechanical, and thermal properties of bio-briquettes produced from king grass which has been torrefied at temperatures of 150˚C, 175˚C and 200˚C. Prior to torrefaction process, fresh king grass was chopped to a size <3 cm, dried under the sun for five days, and then put into the torrefaction reactor with a residence time of 45 minutes. The resulting solid product, i.e. bio-char was then pulverized and sieved to a particle size of 40 mesh, then mixed with 20% wt binder and stirred manually to reach homogeneous. Subsequently, a purposely made press machine was used to produce briquette at a pressure of 150 kg/cm^2 followed by drying the product under the sun for three days. The briquette characterization employed several techniques including thermogravimetry analysis (TGA), differential scanning calorimetry (DSC), bomb calorimeter, and mechanical testing. The results showed that the calorific value of king grass increased from 3747 cal/g to 4346 cal/g after the torrefaction process at a temperature of 175˚C. The results of the proximate test showed that the fixed carbon content increased from 4.76% to 25.75% after the torrefaction process at a temperature of 175˚C. In terms of mechanical properties, it is known that the torrefaction process of king grass has significantly improved the friability, density and size stability. Overall, this study has succeeded in revealing the potential use of briquette products made from king grass as alternative fuel for co-firing at steam power plant.

Keywords:
Biomass, King Grass, Bio-Fuel, Torrefaction, Bio-briquette

1. Introduction

Sustainable and renewable sources of energy are a major topic today due to concerns about depletion of fossil fuel reserves. The use of biomass as fuel is one of the renewable energy sources [1]. Biomass is an ideal alternative as a substitute for fossil energy for environmental friendly energy production. One type of plant that can be used as bioenergy is the king grass plant (Pennisetum Purpupoides) with abundant biomass production levels, good nutritional quality and high environmental adaptability. The potential of king grass can be developed as a biofuel [2]. However, biomass raw materials also have disadvantages, such as high water content, lower calorific value, high volatile content, and low energy density when compared to fossil fuels [3], [4]. It also raises other problems such as emissions during combustion, hygroscopic properties, uneven/heterogeneous composition, and difficulties in transport. [5]. To overcome this problem, biomass needs to be processed further by improving the quality of production of energy conversion materials. Thermochemical conversion of energy from biomass consists of pyrolysis technology [6]–[9], gasification [10]–[12], torefaction [13]–[16], Hydrothermal carbonization [17]–[20], and direct combustion [21]–[24].

Processing technologies such as torrefaction and densification were considered as beneficial strategies to answer the challenges in biomass utilization [5]. Torrefaction is operated under an inert environment at a temperature of 200-300°C known as mild pyrolysis affecting physical and chemical properties. This process partially degrades hemicellulose, cellulose, and lignin while releasing water and certain volatile organic compounds, leading to a significant improvement in biomass quality and more uniform biomass properties [25]. According to Chen et al., torefaction has four main benefits: (1) increase calorific value or energy density, (2) lower water content, hydrogen-carbon ratio (H/C) and oxygen-carbon ratio (O/C), (3) increase resistivity to water and (4) increase reactivity and grindability [26]. Most of research on torrefaction focused on three main aspects in order to improve the torefaction performance, *i.e.* the type of biomass, the temperature of torrefaction and the duration of the torefaction process (residence time).

As mentioned earlier, biomass has a low bulk density which makes the process of transporting and handling difficult. To deal with these shortcomings, densification method can overcome this problem by making biomass to have a high volumetric density and more uniformity in the shape and size [27].

The combination of these two technologies has been reviewed and studied to improve biomass to be used for energy production. Satyanarayana, et.al, explained that the calorific value of straw-based pellets ranges from 17-18 MJ/kg [28]. Neupane et al [29] and Srinivasan et al. [30] discusses the influence of torrefaction parameters such as residence time and temperature on structural changes in pinewood biomass and subsequent influences on product distribution of biomass catalytic torrefaction. Furthermore, Mahadevan conducted tests using pine and switchgrass raw materials at torrefaction temperatures of 150 °C, 175 °C and 200 °C showing that increasing the torrefaction temperature led to an increase in fixed carbon content [31].

Based on recent literature review, it was found that there is still limited use of king grass, especially as solid fuel. So far, no data has been published on the production of bio-briquettes from king grass. Therefore, this study aimed to produce briquettes from king grass through torrefaction process at various temperature *i.e.* 150°C, 175°C and 200°C. Resulting briquettes was then tested to find out the physical and mechanical properties before and after the torrefaction process. The results of this investigation provided beneficial information regarding the physical, thermal and mechanical characteristics of king grass briquettes as sustainable fuel for co-firing in steam power plant.

2. Research Methods

2.1. Biomass Preparation

King grass biomass was collected from the farmer located at Lhokseumawe, Aceh. King grass was chopped into pieces to a size of 3 cm, then dried under the sun for five days. The dried king grass was then placed into torrefaction reactor.

2.2. Torrefaction and Densification

Fig. 1 shows the setup of torrefaction equipment which mainly consisted of a pressure vessel as torrefaction reactor, heating furnace, separators, condenser, un-condensable gas tank and base-frame/ structure. Torrefaction was carried out at temperatures of 150°C, 175°C and 200°C where about one kilogram of dried king grass was placed into the vessel and closed. Heating was then started under atmospheric pressure from room temperature to the desired temperature with a heating rate of 10 °C/ minute and maintained at a final temperature of about 45 minutes. Once the torrefaction process was completed, the solid product was cooled in inert conditions to avoid ignition by air contact. Then, the biochar product was ground and sieved to a particle size of 40 mesh. The refined biochar was mixed with 20 wt% starch binder and stirred manually for 10 minutes until the dough was homogeneous. The dough was then put into briquette mold and pressed up to 150 kg/cm^2 with a holding time of about two minutes. The resulting briquette product was then dried under the sun for three days.

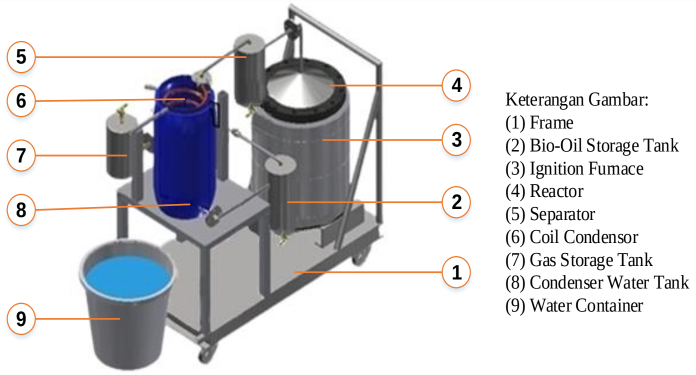


Fig. 1. Set-up of torrefaction equipment

2.3 Product characterization

All prepared samples in this investigation were denoted as explained in Table 1. To understand the characteristics of king grass briquettes, a number of analyses were performed including proximate analysis, Thermogravimetric Analysis (TGA), Differential Calorimetry Analysis (DSC), bomb calorimeter, apparent density, drop test, relaxation test and direct combustion.

Table 1. Sample ID

No	*Sample ID*	Information
1.	KG	Briquette of non-torrified king grass
2.	KGBT 150	Briquettes of torrefied king grass at 150°C
3.	KGBT 175	Briquettes of torrefied king grass at 175°C
4.	KGBT 200	Briquettes of torrefied king grass at 200°C

Proximate analysis were performed to quantify the water, volatile matter, fixed carbon and ash contents following the ASTM D7582-15 procedure [32]. Thermogravimetric analysis (TGA) and Differential calorimetry analysis (DSC) were assessed under Shimadzu DTG-60 and Shimadzu DSC-60 machines by purging with oxygen at a flow rate of 20 ml/min and a heating rate of 10°C/min. The sample was placed in an alumina container *c.a.* 10 mg, then heated from ambient temperature to 1000°C. Koehler K88990 Bomb-type Calorimetry was used to analyse the caloric value of the king grass briquettes. Apparent density was determined from the total volume of the briquettes divided by the total weight of sample after drying.

Mechanical properties of the briquette products were also carried out through dropped test. This test followed the ASTM D440-86 procedure with aiming to find out the resistance of briquettes when dropped from a height of 1.8 m on hard and flat surfaces. The mass of briquettes was measured before and after the test using digital scales with an accuracy of 1/1000 gram [33]. Due to a tendency of briquettes to expand after pressing, the changes in size of the briquettes after densification process was measured following ASAE S269.4 DEC96 protocols [34]. The parameters measured were height and diameter once every one minute until the values were constant.

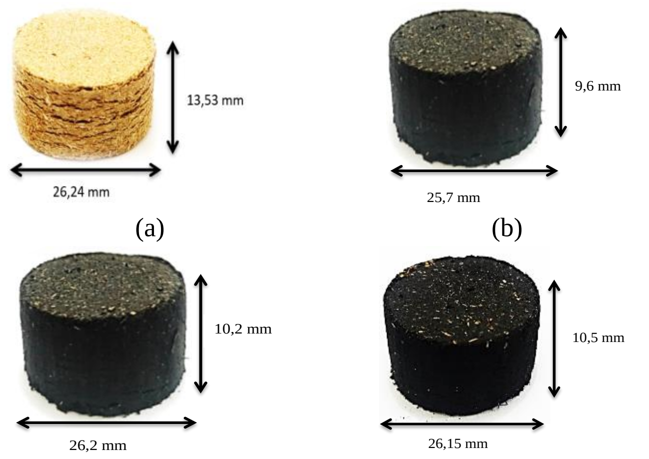
Direct combustion tests were carried out according to the method proposed by Quirino [35]. About 50 g of king grass briquettes are used and placed in the combustion chamber and ignited by 20 g of ethanol. The use of ethanol at the beginning of the test did not affect the results. During the test, the mass and temperature changes were recorded every minute. Fig. 2 shows the picture at which the combustion test taking place.

(a) (b) (c)

Fig. 2. Combustion tests.(a) image of briquette sample before burning; (b) photograph when the briquettes were firing; and (c) photograph when the briquettes at the end of the combustion process.

3. Result and discussion

Fig. 3 shows the images of all briquette products after drying process. The un-torrified king grass briquette as shown in Fig. 3a has a diameter of 26.24 mm and height of 13.53 mm. The briquettes produced after torrefaction process at temperatures of 150°C, 175°C and 200 °C have diameter within the range of 25.7 mm to 26.2 mm. The height of torrified king grass briquettes were respectively 9.6 mm, 10.2 and 10.5 mm for KGBT 150, KGBT 175 and KGBT 200.



(a) (b)

(c) (d)

Fig. 3. Images of product and sizes/ (a) KG; (b) KGBT 150; (c) KGBT 175 and (d) KGBT 200

Based on images in Fig. 3, it can be learnt that the torrefaction process led to the changes in final size of the product. This is nearly similar to those reported in the literature [36]. The difference in height of briquettes which produced with torefaction process compared with those produced without torrefaction is mostly due to removal of lignocellulose content [37]. Torrefaction process helped in increasing the density of the raw material as well as the final product.

3.1. Physical and Mechanical Properties

The results of the proximate analysis of king grass briquettes are shown in Table 2. In general, king grass briquettes contain more volatile matter than fixed carbon. Fixed carbon content of KG briquette was significantly lower than KGBT briquettes. This means torrefaction process has improve the fixed carbon content and decreased the amount of volatile matter. As reported by Setter, et.al, the percentage of fixed carbon has direct correlation with lignin content in lignocellulose biomass and positively affects the calorific value [36].

Table 2. Proximate analysis results

Parameter	KG	KGBT 150	KGBT 175	KGBT 200
Proximate analysis				
Moisture content (%)	8.51	5.89	5.8	5.55
Ash content (%)	11.63	27.73	22.58	24.23
Volatile matter (%)	75.1	40.97	45.86	45.67
Fixed carbon (%)	4.76	25.41	25.75	24.54
Size stability (%)	98.15	99.28	98.82	99.37
Friability (%)	1.87	0.72	1.19	0.64
Apparent density (g/ml	0.472	0.972	0.793	0.756
Caloric value (cal/g)	3747	4324	4346	4069

The results of the drop test show that the higher the temperature in the torefaction process, the lower the friability of the briquettes. This is due to a more stable density level [38], [39]. However, in contrast to the apparent density analysis, it shows that the higher the torrefaction temperature, the lower the briquette density. On the other hand, the caloric value of briquette after torrefaction increased significantly from 3747 cal/g to to 4324 cal/g. From the relaxation test results data in Fig. 4 shows that the expansion of the briquette volume after being removed from the pressing machine indicates that the higher the torefaction temperature of king grass biomass, the greater the change in the volume of briquettes. This is in good agreement with the argument explained in the literature [40].

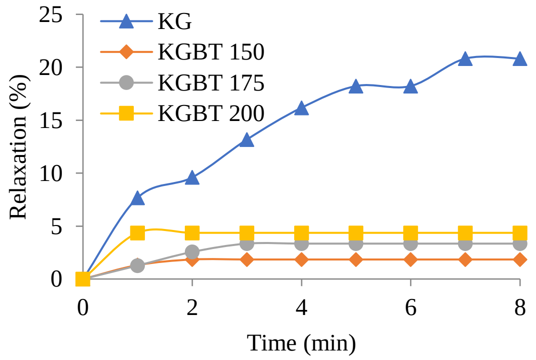


Fig. 4. The changes in volume of briquettes with and without torrefaction

3.2. Thermal analysis

The thermal analysis of king grass briquettes was carried out under thermogravimetric analysis in order to understand the combustion thermal and combustion characteristics of briquettes. Fig. 5 displays the thermogram curves of torrefied king grass which was densified at various pressure.

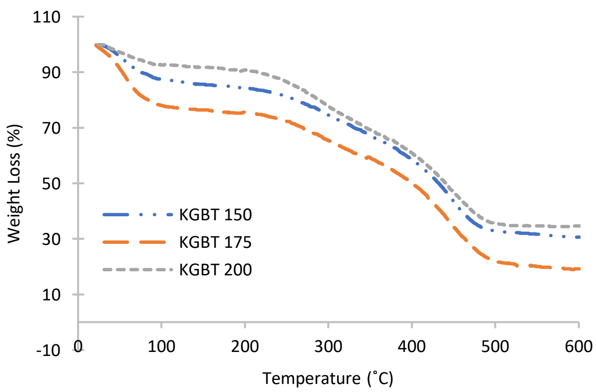


Fig. 5. TGA curves of torrefied king grass briquettes at various pressures

During combustion test under TGA, sample was heated under air flow from room temperature to 600°C. At any curves it can be observed that there are three stages of process occurred during the experiment. The first stage taken place as drying process where moisture and organic matters with a low boiling point within the sample were decomposed. At this stage, the drying process (burning loss of moisture content) occurs with a weight loss of 8%-24% to a temperature of 120°C. The second stage is oxidation of volatile compounds where the weight loss was between 15% to 19% at temperature up to 366°C. The third stage is char combustion which is characterized by a very sharp decrease in mass then slows down and tends to stabilize. In this process there is a decrease in mass weight by 36-40% and occurs up to a temperature of 524 °C. At a temperature of 530-600°C the curve has begun to be stable since no longer combustion process taken place within this temperature range. All that remains was the ash content [41].

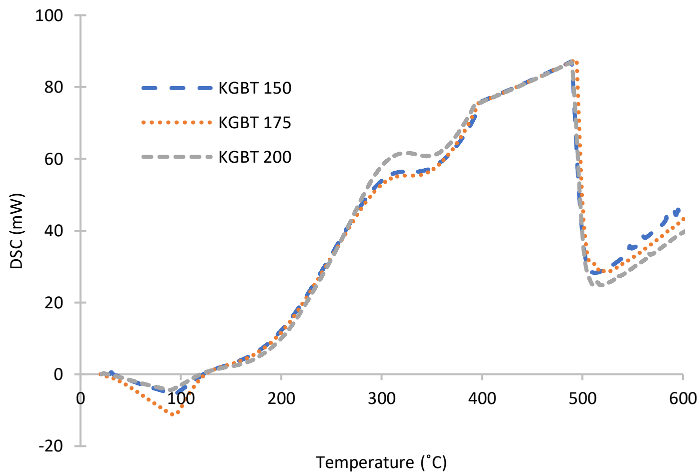


Fig. 6. DSC curves of torrefied king grass briquettes

Fig. 6 shows the DSC curve of torrefied king grass briquettes. During this experiment, sample was heated under air flow at 20 ml/min from room temperature to 600 °C. In general, endothermic reaction was occurred at temperatures lower than 135°C. This is due to water vapor decomposition as characterized by an endothermic peak where the area under the peak is qual to the amount of energy required decompose water content. At temperature above 140°C, exothermic reaction taken place reaching the maximum at 490°C. All combustible compounds were oxidized at this stage where the sample reacted with oxygen to produce ash. The DSC curves show that the overall decrease in heat flow indicating that the main components of biomass are actively changing at a temperature of <600°C is similar as reported [42], [43].

3.3. Direct combustion test

In order to find out the actual rate of combustion and temperature, direct combustion test was carried out following the method proposed in the literature [35]. About four grams of briquette sample was placed on the tray and ignited with a few drops of gasoline. The combustion test was performed less than 30 minutes where sample weight loss and temperature changes were collected every minute. The recorded data was plotted to established correlation curves between weight loss vs time and temperature vs time. The same parameters were adopted for bulk coffee husk combustion test [36] for comparison purposes.

The thermal behaviors of briquettes during combustion tests are shown in Fig. 7 and Fig. 8. For KGBT 150, KGBT 175 and KGBT 200 samples, the combustion duration occurred within the range of 22 minutes to 28 minutes, while burning KG briquette was finished within 17 minutes. Based on these curves, it can be learnt that the higher the temperature of torrefaction, the longer the duration of combustion of the briquette product. At each experiment, the highest temperature was detected within first five minutes combustion where the combustion temperature was within the range of 400°C to 420°C. During the tests it also can be observed that the residence time at high temperatures stayed only a few minutes, then slowly decreased. All samples were easy to burn and there is no significant difference in terms of the rate of combustion.

Combustion behavior indeed is influenced by the chemical and physical characteristics of lignocellulose materials, such as chemical composition (cellulose, hemicellulose and lignin), elemental content (CHNS-O), ash, moisture content, surface area and pseudo-density. Hemicellulose and cellulose contribute to devolatilization during the combustion of lignocellulose materials and therefore support the yield of volatile gases. On the other hand, lignin, since it is more stable, favors the yield of solid fractions. In relation to the elemental composition, the elements hydrogen and oxygen present in lignocellulose biomass contribute to the initial ignition in the combustion process [36], [44].

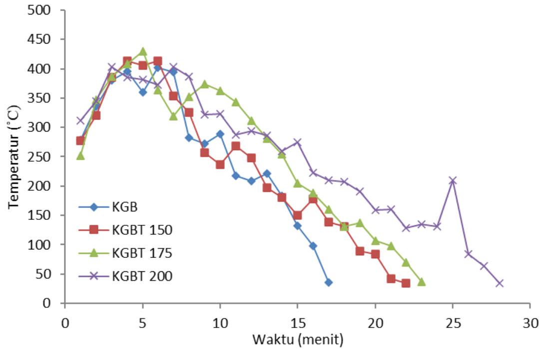


Fig. 7. The curve of changes in combustion temperature over time

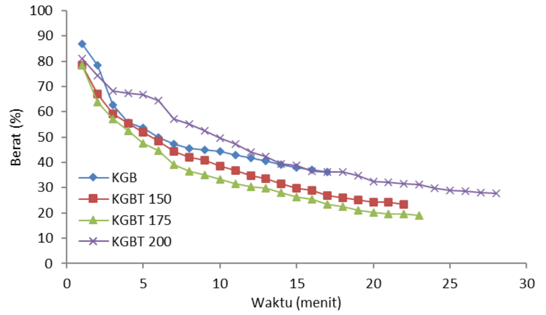


Fig. 8. Weight loss curve against time during the briquette burning process

4. Conclusion

This study has examined the effect of torrefaction temperature on the physical, mechanical and thermal properties of bio-briquettes derived from king grass biomass. The results of the analysis show that in general the torrefied briquettes have better quality compared to those prepared without torrefaction. The highest fixed carbon content and calorific value were obtained from densified king grass which was torrefied at 175°C (KGBT 175), *i.e.* 25.75% and 4346 cal/g, respectively. Direct combustion tests suggested that increasing the torrefaction temperature, increases the duration of combustion. In terms of mechanical properties, the torrefaction process enhances significantly the friability, density and size stability of the briquettes. Finally, this study has successfully revealed the potential use of king grass biomass as feedstock for bio-briquette production.

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