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Effect of briquetting pressure on combustion properties of hydrothermally treated king grass biomass

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Abstract

The utilization of biomass as an alternative energy source continues to gain attention, particularly in the form of solid briquettes with properties comparable to coal. In Indonesia, the co-firing program in coal-fired power plants promotes the use of biomass briquettes as supplementary fuel. King grass (Pennisetum purpureum), a fast-growing, non-food crop that thrives on marginal land, is a promising candidate. However, its low energy density limits practical application. This study aims to enhance the fuel quality of king grass through hydrothermal treatment and evaluate the effect of varying briquetting pressures on briquette properties. Briquettes were produced without pressure and with compaction pressures of 100, 200, 300, 400, and 500 kg/cm^2. Results show that higher briquetting pressure reduced moisture content from 3.99% to 2.98% and friability from 54.46% to 11.95%. While ash content and volatile matter were minimally affected, fixed carbon increased to 28.42%, and calorific value peaked at 3,923 kcal/kg. Hydrothermal treatment further improved calorific value, reduced ash content, and enhanced fixed carbon levels. These findings demonstrate that the combination of hydrothermal treatment and briquetting pressure significantly improves king grass briquette quality, supporting their potential as a sustainable co-firing fuel in coal-fired power plants.

Keywords:
Bio-briquette, ash content, calorific value, king grass, hydrothermal

1 Introduction

Significant climate change is occurring worldwide, primarily driven by increasing greenhouse gas emissions, especially from the energy sector [2]. Globally, energy consumption rose to 418 EJ in 2019 and is projected to increase to 516 EJ by 2040, equivalent to a 23% rise [3]. The development and use of biofuels has gained widespread acceptance due to their carbon-neutral and sustainable nature. The biorefinery process for biofuel production involves various physical, chemical, and biological techniques to convert biomass into biofuels.

One underutilized yet promising biomass source is king grass (Pennisetum purpureum), a lignocellulosic biomass plant with high potential as a raw material for biofuel production [4]. This plant is easy to grow on marginal lands, highly productive, environmentally beneficial, easy to process, and does not compete with food crops [5], and can be harvested several times a year [6].

One of the main drawbacks of biomass is its low bulk density, high moisture content, and low energy density. Therefore, processing techniques such as hydrothermal treatment and densification are required. Hydrothermal processing is considered a key pretreatment method, as it affects the chemical, energetic, and physical properties of biomass. Hydrothermal processing is a thermochemical conversion method that transforms biomass into high-value products such as biofuels. This process is typically conducted in water at temperatures between 250–374°C and pressures of 4–22 MPa. One of the main advantages of this method is its ability to process high-moisture biomass without the need for pre-drying [7].

According to Tekin *et al.* [8], hydrothermal treatment is an effective method to enhance biomass quality, carried out in a hot water medium with an energy consumption of approximately 2 kW in their experiments. Through hydrothermal processing, the moisture content of the biomass is reduced, thereby increasing its calorific value. The hydrothermal process is influenced by temperature, pressure, and reaction time. Each type of biomass and coal has its own optimal hydrothermal processing conditions. Besides reducing moisture content, hydrothermal treatment can also modify the physical and chemical characteristics of biomass. Hydrothermal carbonization is considered a cost-effective method for producing hydrochar, as it can be conducted at relatively low temperatures (around 180-350°C). This method uses liquid as both the solvent and catalyst under pressure. The charcoal-like product produced through hydrothermal processing is referred to as hydrochar. Additionally, adding substances such as sulfuric acid, acetic acid, or lithium chloride to the liquid medium can enhance the efficiency of the hydrothermal process [9].

One approach to increase the energy content of biomass is by converting it into bio-briquettes through densification. According to Ito *et al.* [10]. The composition and type of materials used in briquette production significantly influence the characteristics of the briquettes, including their calorific value, combustion duration, and burning rate. Without densification, it is difficult to significantly increase the energy content of biomass. Densification not only reduces the void spaces in the raw material but also increases the calorific value, mechanical strength, and durability of bio-briquettes. Moreover, densification can reduce moisture content and improve energy content [11].

Granado *et al.* [12] shows that compaction pressure on cassava waste with pressure variations of 102, 153 and 204 MPa can increase the energy density by 2.04 GJ/m3. With compaction, an energy density of 15.7 GJ/m^3 is obtained, which shows an increase of up to 7.7 times. We obtained a higher durability (94.1%) for a pressing time of 120 seconds and a pressure of 204 MPa. The results of this study, Cavallo *et al.* [13] indicate that pressure levels - in the range of 20-110 MPa - significantly affected the final quality of the briquettes: the higher the pressure, the higher the quality of the briquette. Moreover, the study highlighted that the final density value is strongly affected by the kind of biomass and by the different properties of the materials.

Research Rifanida *et al.* [1] showed that king grass subjected to torrefaction at 150, 175, and 200°C resulted in calorific values of 4324 cal/g, 4346 cal/g, and 4069 cal/g, respectively. Meanwhile, Gao *et al.* [14] studied a hydrothermal reactor prototype to process waste into solid fuel. Their tests were conducted at hydrothermal temperatures of 130, 150, 170, and 190°C, and stirring speeds of 0, 250, 300, and 350 rpm. The results showed the highest calorific value of 6898 kcal/g at 190°C. Proximate analysis revealed a moisture content of 13.19%, volatile matter at 53.04%, ash content at 9.08%, and fixed carbon at 24.69%.

While hydrothermal carbonization pre-treatment enhances fuel quality, there is are lack of comprehensive studies on the effect of briquetting pressure on hydrochar made from king grass. This provides a stronger foundation for our studies' purpose. Based on the explanations above, this study utilizes king grass biomass with hydrothermal carbonization as a pre-treatment before bio-briquette production to enhance its calorific value. The objective of this research is to evaluate the effect of varying briquetting pressures on the combustion characteristics, density, durability, and thermal behavior of king grass briquettes. It is expected that these briquettes can eventually be used as co-firing fuel in coal-fired power plants.

2 Materials and methods

2.1 Raw material preparation

King grass was obtained from community plantations in Blang Pulo Village, Lhokseumawe City, Aceh. The raw material was sun-dried for four days to reduce part of its moisture content. After drying, the king grass was cut into pieces measuring 3-5 cm using a chopper machine, then ground and sieved to pass through a 20-mesh screen.

2.2 Hydrothermal preparation

Wet torrefaction was carried out using an autoclave reactor made of stainless steel, model 47-MaXterile, operated electrically at 230V AC, 50–60 Hz, with a maximum pressure of 3.0 bar (g). King grass that passed through a 20-mesh sieve was placed into a beaker and mixed with distilled water at a 1:5 ratio until fully submerged. The beaker glass was then placed inside the autoclave reactor with deionized water used as a controlling medium.

The hydrothermal process was conducted for 90 minutes at a pressure of 2 atm and a temperature of 130°C. After the process was complete, the reactor was cooled to room temperature. The reactor was then opened, and the hydrochar product was collected. The hydrochar was pressed to remove residual moisture from the hydrothermal process.

The pressed hydrochar was then mixed with 5% tapioca flour as a binder. The resulting mixture was molded into briquettes using a briquetting machine with a mold size of 30 × 30 mm, as shown in Fig. 1, and closed with a mold cap. The cap was locked, and the mixture was compacted under pressures of 100, 200, 300, 400, and 500 kg/cm². The briquettes were sun-dried for 2–3 days. Subsequently, the briquettes were tested for proximate analysis, calorific value, density, durability, stability, and combustion rate.

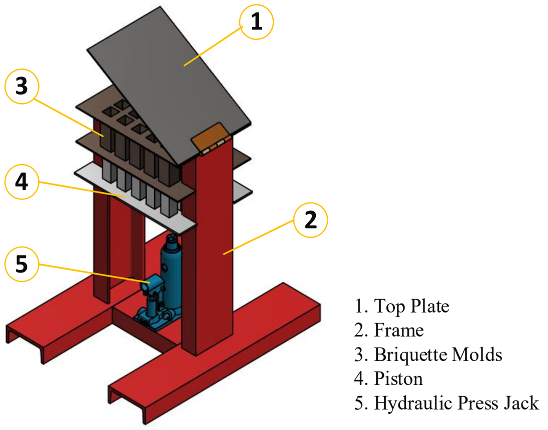


Fig. 1. Briquette pressing machine

The samples used in this study consisted of six different briquette types, as described below. BKG refers to king grass briquettes without hydrothermal treatment. HKG100 refers to briquettes produced with hydrothermal treatment and compacted at a pressure of 100 kg/cm², HKG200 at 200 kg/cm², HKG300 at 300 kg/cm², HKG400 at 400 kg/cm², and HKG500 at 500 kg/cm².

2.3 Characterization

Proximate analysis included moisture content testing using a Memmert UN 30 oven (Germany), and ash and volatile matter content testing using a Bench Furnace model BF 02-/27. Proximate analysis was conducted according to the procedures specified in the Indonesian National Standard (SNI 01-6235-2000) [15]. The calorific value was analyzed using a Koehler K88900 bomb-type calorimeter.

Apparent density was determined based on the external volume of the briquettes. A mechanical instrument, such as a micrometer, was used to measure different sides of the briquette to calculate the outer volume. Drop resistance tests were carried out using a free-fall method to evaluate the briquettes' resistance to impact when dropped from a height of 1.8 meters onto a hard, flat surface. The drop test followed the ASTM D440-86 procedure. The mass loss of the briquettes before and after testing was measured using a digital scale with a precision of up to 1/1000 gram [16].

Combustion tests were performed following the method proposed by Quirino [17]. Approximately 50 grams of king grass briquettes were placed inside the combustion chamber, and 20 grams of ethanol were used in an aluminum container as an ignition aid. The use of ethanol during ignition did not affect the test results. The analysis lasted for 17 minutes, with mass and temperature data recorded every minute.

3 Results and discussions

3.1 Physical characterization of king grass briquettes

Fig. 2 shows the king grass briquette products from the hydrothermal process after drying. Briquetting is an essential method in biomass conversion, transforming biomass into a denser form that is more efficient for storage and readily usable as fuel. The variation in compaction pressure plays a crucial role in determining key physical properties of the briquettes, such as dimensions and density. At lower pressures, such as 100 kg/cm², the resulting briquettes tend to have greater height and lower density because the king grass particles are not yet well-compressed. In contrast, at higher pressures, like 400 and 500 kg/cm², the biomass particles undergo intense compression, resulting in more compact briquettes with smaller sizes. This indicates that increasing the briquetting pressure significantly affects the dimensions and density of the briquettes, which are key indicators of fuel quality.

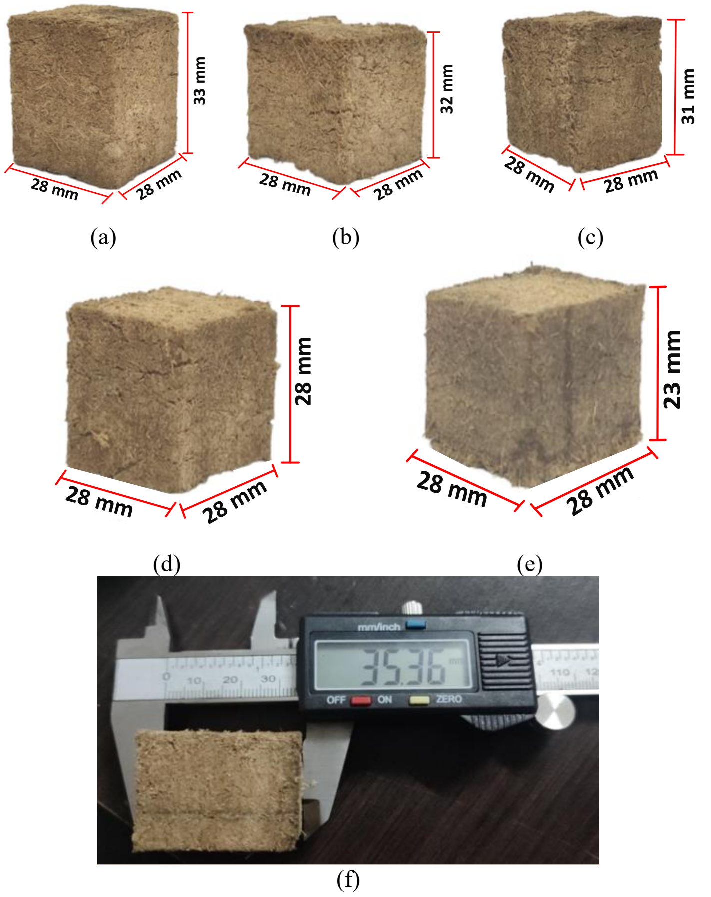


Fig. 2. King grass briquettes with varying compaction pressures: (a) HKG100; (b) HKG200; (c) HKG300; (d) HKG400; (e) HKG500; and (f) BKG

The reduction in briquette height at higher compaction pressures indicates that the interaction between biomass particles becomes stronger, thereby increasing the briquette density. Denser briquettes generally exhibit better combustion performance due to the reduced void space between particles, which can otherwise hinder the burning process. In addition, higher density can enhance the briquette's resistance to physical damage. As stated by Eling *et al.* [16], factors influencing the biomass briquetting process include pressure, temperature, and material composition. Table 1 presents the physical properties of five king grass briquettes (HKG100, HKG200, HKG300, HKG400, and HKG500). These properties were compared with data from the BKG sample.

Table 1. Physical and mechanical properties of hydrothermal king grass bio-briquettes

Parameter	Unit	Sample ID					
		BKG	HKG100	HKG200	HKG300	HKG400	HKG500
Moisture content	%	5.09	3.99	3.76	3.57	3.1	2.98
Ash content	%	6.69	3.29	3.59	3.18	3.44	3.37
Volatile matter	%	69.97	69.18	68.71	69.28	69.47	65.23
Fixed carbon	%	18.25	23.54	23.94	23.97	23.99	28.42
Apparent density	g/cm^3	0.472	0.312	0.315	0.317	0.34	0.43
Size stability	%	98.15	45.54	63.91	75.12	78.96	88.05
Friability	%	1.87	54.46	36.09	24.88	21.04	11.95
Caloric value	cal/g	3747	3793	3793	3891	3790	3923

The moisture content of the briquettes tended to decrease with increasing briquetting pressure compared to BKG [1]. The BKG sample had the highest moisture content at 5.09%, while HKG500 had the lowest at 2.98%. This reduction indicates that increased briquetting (hydraulic compaction) pressure leads to lower moisture content in the briquettes. Lower moisture content helps minimize incomplete combustion and increases the calorific value of the briquettes. This aligns with the purpose of the hydrothermal process, which not only reduces moisture but also enhances briquette density and compaction.

According to Wang et al. [18], the compaction and hydrothermal treatment processes can lower the moisture content of biomass materials, thereby potentially improving fuel quality. This finding is also supported by Granado et al. [12], who reported that higher compaction pressure leads to lower moisture content. High moisture content can also result in excessive smoke during combustion and hinder ignition. Additionally, elevated moisture levels can promote mold growth on briquettes, negatively impacting storage quality. The variation in briquetting pressures applied in this study meets the quality standards for bio-briquettes as specified in SNI 01-6235-2000, which require a moisture content of ≤ 8%.

The ash content before the hydrothermal process (BKG) was 6.69%, and after hydrothermal treatment, it decreased by approximately 3%, ranging between 3.18% and 3.59%. The highest ash content was found in HKG200 (3.59%), while the lowest was observed in HKG300 (3.18%). This reduction is attributed to the hydrothermal process, during which certain compounds in the raw material migrate into the liquid medium, resulting in a lower ash content in the final briquette product.

Ash is generally considered an undesirable component in briquette characteristics, as it is inert and acts as an inhibitor of high calorific value in the product [19]. Moreover, high ash content can lead to slagging or fouling and may reduce the quality of the briquettes by lowering both the calorific value and the combustion rate. With the five different briquetting pressures applied in this study, the ash content of the briquettes meets the quality standards specified in SNI 01-6235-2000, which require an ash content of ≤ 8%. The analysis showed that the ash content of the raw material was 6.69%, but after undergoing the hydrothermal process, the ash content decreased significantly to around 3%, and no significant changes were observed with increasing briquetting pressure. This indicates that the hydrothermal process is effective in reducing ash content, which in turn can improve the combustion quality of the briquettes. This finding is supported by previous investigations reported in the literature [19], [20].

The volatile matter content remained relatively stable across all briquette samples, with a slight decrease observed in HKG500 at 65.23% compared to BKG at 69.97%. This reduction in volatile matter may be attributed to the hydrothermal process, where higher thermal input can slightly reduce volatile content due to dehydration and structural changes in the biomass. Volatile matter is a key parameter related to fuel reactivity during combustion.

A decrease in volatile matter can enhance combustion stability, although it may also affect the energy performance of the briquettes. Monedero et al. [21] stated that reducing volatile matter in briquettes can improve combustion stability and reduce harmful gas emissions. A higher volatile matter content typically results in easier ignition and faster combustion rates. While high volatile content offers advantages such as ease of ignition and combustion, it also has drawbacks, particularly lower fixed carbon content. Furthermore, a high volatile matter content in bio-briquettes can lead to excessive smoke during ignition, contributing to increased carbon emissions.

The fixed carbon content increased with higher briquetting pressure, indicating that the hydrothermal process enhanced the fixed carbon content in the briquettes. This is directly related to the improvement in energy quality, as fixed carbon significantly contributes to combustion energy. An increase in fixed carbon content can enhance the calorific value of the briquettes, since fixed carbon serves as the primary fuel component during combustion.

The calorific value increased slightly with rising briquetting pressure, from 3,793 cal/g in HKG100 to 3,923 cal/g in HKG500. This suggests that the increase in fixed carbon and the reduction in moisture content contributed to the improvement in calorific value. Additionally, the calorific value is also influenced by the ash content of the bio-briquettes, where high ash content corresponds to a lower calorific value, and conversely, lower ash content tends to result in a higher calorific value [11]. A higher calorific value indicates better combustion efficiency and greater energy output from the briquettes. The reduction in moisture content and the increase in fixed carbon were achieved through the hydrothermal process, which helps optimize the energy performance of the briquettes. Granado et al. [22] stated that briquettes with higher calorific value have certain advantages, including slower combustion due to the reduced presence of moisture and volatile matter that otherwise accelerate the combustion process and mass loss during burning.

Apparent density increased significantly with higher briquetting pressure, resulting in denser briquettes. This is because greater compaction pressure forces the particles to fill voids more effectively, thereby increasing the overall density of the briquette [23]. Eling et al. [24] indicated that increasing the density of biomass can reduce volume, which contributes to improved energy quality of the briquettes and enhances the efficiency of fuel transportation and usage. Low-density briquettes present limitations in packaging, storage, and transportation, as they are more susceptible to breakage under pressure due to their weak structural integrity. Density also plays a critical role in the combustion process. Briquettes with lower density tend to burn more quickly, while those with higher density burn more slowly. High density also contributes to greater mechanical strength, making briquettes easier to package, more resistant to external pressure, and less prone to crumbling.

Size stability increased with higher compaction pressure, which can be attributed to the fact that greater pressure during the hydrothermal process reinforces the briquette structure, making it stronger and more resistant to damage. As density increases, less mass is lost during the drop test. Overall, the size stability ranged from 45.54% to 88.05%. High-size stability in briquettes compressed under higher pressure enhances their durability during packaging, distribution, and storage. The densification process strengthens the briquette matrix, resulting in briquettes with better dimensional stability, reducing the risk of breakage and improving combustion efficiency [25].

Friability is inversely related to size stability, with briquette fragility decreasing as compaction pressure increases. The HKG500 sample exhibited the lowest friability at 11.95%, indicating that denser, more compressed briquettes have better resistance to physical damage. Dense briquettes with low friability offer advantages in mechanical strength, which is crucial for transportation and long-term use. The increase in mechanical strength results in a more stable product that is easier to handle and operate [25].

The hydrothermal process applied to king grass briquettes demonstrated that higher briquetting pressures significantly influence briquette quality, resulting in increased density, fixed carbon, and calorific value, along with decreased moisture content, ash content, and volatile matter. These changes lead to improved combustion efficiency and enhanced briquette durability.

3.2 Combustion rate of king grass briquettes

Combustion testing was conducted to evaluate the effectiveness of the fuel. This assessment aims to determine the feasibility of the tested fuel for practical application. The combustion rate of bio-briquettes refers to the speed at which the briquettes are completely burned to ash. A higher combustion rate indicates that the briquette burns more quickly and is consumed faster. The results of the combustion rate test for the bio-briquettes are presented in Fig. 3.

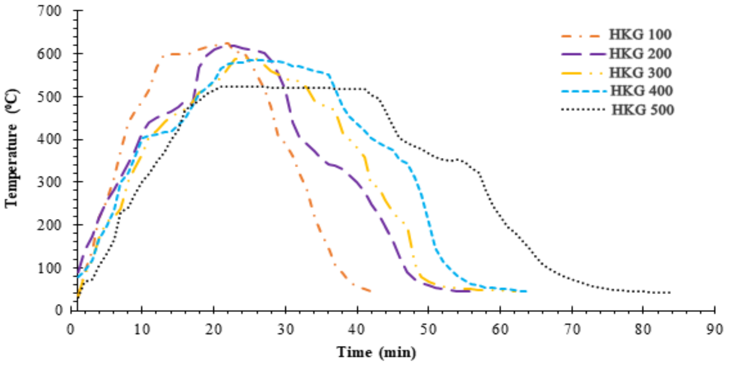


Fig. 3. Temperature profile of briquettes over combustion time

Fig. 3 presents the combustion temperature curve of hydrothermally treated king grass bio-briquettes over the duration of the testing period. The curve illustrates the decline in briquette mass from ignition to complete conversion into ash. The briquette with the longest combustion time was HKG300, burning for 46 minutes with a combustion rate of 0.45 g/°C. The combustion durations for other briquettes were as follows: HKG100 – 40 minutes, HKG400 – 38 minutes, HKG500 – 34 minutes, and HKG200 – 31 minutes.

A significant mass loss occurred between minutes 1 and 16, as shown in Fig. 4, indicating that this sharp decline was primarily due to the high volatile matter content in the bio-briquettes. As illustrated in Fig. 5, the highest mass loss occurred in the HKG200 sample, which had a volatile matter content of 69.185%. The differences in mass loss and combustion time were influenced by the calorific value and volatile matter content of the bio-briquettes. Higher volatile matter content enhances ignition and burning ease; however, it also tends to produce more smoke during combustion [26]. Briquette density also plays a critical role in mass reduction. Low-density briquettes burn faster due to the greater void space, which facilitates more rapid combustion. Mass loss increases with rising briquette temperature, and once the briquette reaches its optimum temperature, the mass reduction rate accelerates further.

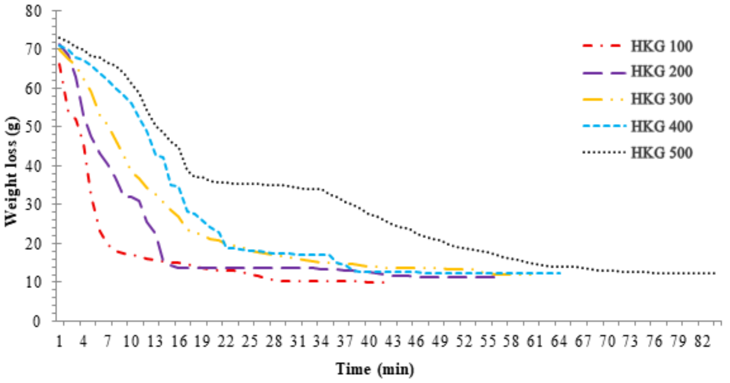
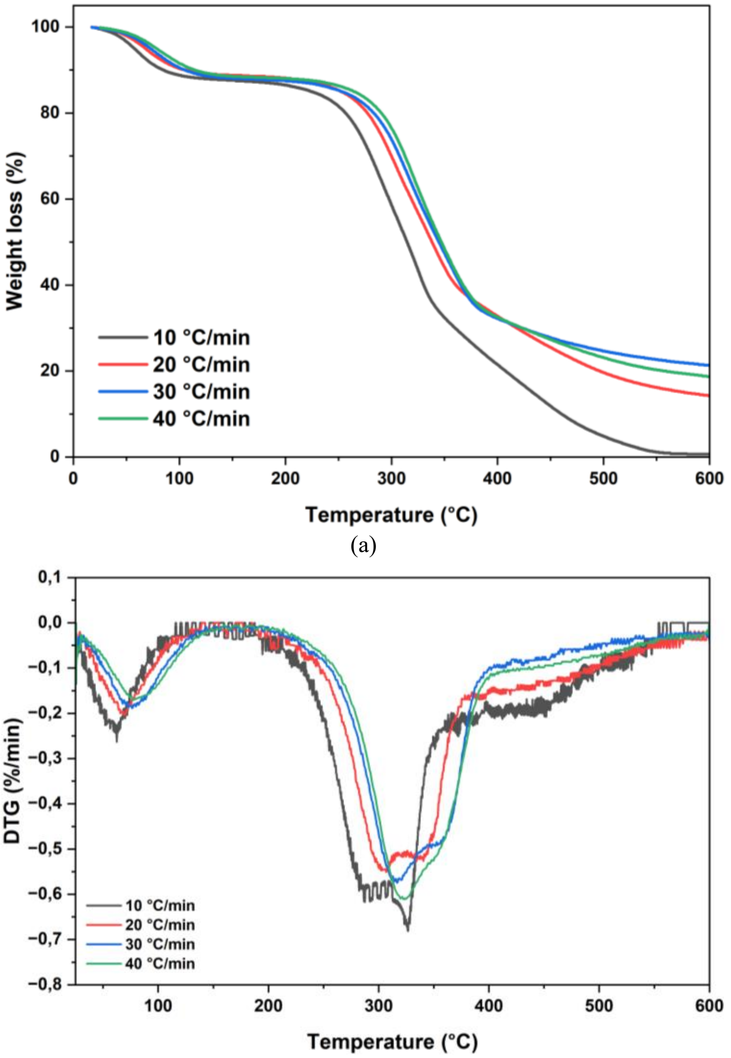


Fig. 4. Mass loss profile of briquettes over combustion time



(a)

(b)

Fig. 5. (a) TGA and (b) DTG curves of hydrothermal king grass bio-briquettes

The relationship between combustion duration and peak temperature observed in this study appears to be contradictory. HKG200 produced the highest peak temperature, yet had the shortest combustion duration. In contrast, the HKG300 exhibited a longer combustion time but a lower peak combustion temperature.

The combustion rate indicates how quickly a briquette burns over a given period. Briquettes produced under higher compaction pressures showed slower combustion rates. For instance, the combustion rate of HKG100 was recorded at 1.271 g/min, which decreased to 0.748 g/min in HKG500. This decrease suggests that briquettes compressed at higher pressures tend to burn more slowly and more efficiently, enhancing both energy quality and combustion duration. Briquettes with slower combustion rates are generally considered more efficient, as they allow more energy to be extracted during burning and help reduce pollution. A slower combustion rate also reflects better stability during combustion, which is beneficial in terms of energy efficiency. Adam *et al.* [27] noted that increasing briquetting pressure can reduce the combustion rate of briquettes, indicating more controlled and efficient combustion as well as reduced emissions.

3.3 Thermal analysis

Fig. 5 presents the TGA and DTG curves of king grass briquettes at four different heating rates: 10, 20, 30, and 40°C/min. The TG curve (Fig. 5(a)) illustrates the pyrolysis behavior of the king grass briquettes, showing distinct thermal phases at each heating rate. The results indicate that the pyrolysis process for all samples can be divided into three main stages: dehydration, devolatilization, and carbonization [28], [29].

The first stage, dehydration, occurs between 40–150°C and is attributed to the degradation of lightweight components, including moisture and light volatile substances. At this stage, briquette weight loss reaches approximately 12%. The second stage, devolatilization, occurs between 150–400°C, where volatile components such as hemicellulose, cellulose, and parts of lignin begin to decompose. At higher heating rates (30 and 40°C/min), devolatilization shifts to higher temperatures. Beyond 400°C, the third stage involves the stable decomposition of lignin, with a slower rate of mass loss.

Fig. 5(b) shows the corresponding DTG curves, where the peak related to moisture evaporation can be observed in this temperature range. The evaporation of water creates crack-like fissures on the briquette surface, which act as pathways for pyrolysis gases to escape during subsequent thermal decomposition stages [30]. According to the study conducted by Kuthe *et al.* lignocellulosic materials with a moisture content below 15% are considered suitable for briquetting as combustion fuel [31].

The second stage, devolatilization, occurs between approximately 150°C and 400°C and results in the greatest weight loss during thermal degradation—up to 66%. As shown in Fig. 5(a), increasing the heating rate clearly shifts this stage to the right, indicating that higher temperatures are required to decompose hemicellulose and cellulose [29]. This demonstrates that the heating rate affects the combustion reaction kinetics; at faster heating rates, heat is distributed less uniformly within the sample, requiring higher temperatures for degradation to occur.

This shift is more apparent in the DTG curves, where the peak temperature increases from 305°C to 319°C and then to 324°C as the heating rate increases from 20°C/min to 30°C/min and 40°C/min, respectively. In the third stage, carbonization, mass loss occurs from 400°C to 600°C. During this phase, lignin in the briquettes decomposes, and weight loss continues until only hydrochar residue remains at the maximum decomposition temperature [29]. A higher amount of hydrochar residue is positively correlated with a Higher Heating Value (HHV).

4 Conclusion

This study produced and characterized hydrochar briquettes from king grass under different briquetting pressures. Increasing briquetting pressure effectively reduced moisture content from 3.99% to 2.98% and friability from 54.46% to 11.95%, enhancing the mechanical stability of the briquettes. Although briquetting pressure showed minimal influence on ash content and volatile matter, it contributed to increased fixed carbon (up to 28.42%) and a higher calorific value, reaching 3,923 kcal/kg. The HKG300 sample exhibited the longest combustion duration of 46 minutes with an optimal combustion rate of 0.45 g/°C, indicating improved burning stability. The hydrothermal carbonization process itself also enhanced calorific value, lowered ash content, and raised fixed carbon levels, thereby improving the overall fuel quality of king grass. These results confirm that the integration of hydrothermal treatment with mechanical compaction offers a practical method for producing higher-quality biomass briquettes. Consequently, hydrothermally treated king grass briquettes can be a strong potential as a sustainable co-firing fuel for coal-fired power plants in Indonesia.

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