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Combustion Performance and Physicochemical Characteristics of Sawdust-Based Bio-Charcoal Briquettes using Molasses Adhesive

Andi Chairil Ichsan[*], Rima Vera Ningsih, Dwi Sukma Rini, Kornelia Webliana

Department of Forestry, Faculty of Agriculture, University of Mataram, West Nusa Tenggara, Indonesia
[*] Corresponding Author. E-mail address: andi.foresta@unram.ac.id

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ABSTRACT

Bio-charcoal briquettes are a promising alternative to fossil fuels, particularly when produced from biomass waste such as sawdust. This study investigates the effects of varying molasses adhesive concentrations (5%, 10%, and 15%) on the physical and chemical properties of bio-charcoal briquettes produced from sawdust. The briquettes were analyzed for density, moisture content, ash content, volatile matter, fixed carbon, and calorific value. Scanning Electron Microscopy (SEM) and Fourier Transform Infrared Spectroscopy (FTIR) were also employed to examine surface morphology and functional groups. The results showed that increasing molasses concentration led to higher density, moisture content, and fixed carbon content, while reducing ash and volatile matter content. The 10% molasses concentration provided the highest calorific value (5,420 cal/g). The results of testing using SEM with a magnification of 2000x, featuring a particle size of 60 mesh, revealed the morphology of the briquette surface with a regular arrangement of cavities. FTIR analysis confirmed the presence of O-H, C-H, and C=O groups, which contribute to molecular bonding. All samples met the SNI 01-6235-2000 standard for wood charcoal briquettes. The addition of 1% potassium chlorate further improved ignition and combustion. The findings demonstrate that molasses, as a low-cost and eco-friendly binder, effectively enhances the quality and energy performance of bio-charcoal briquettes. This study supports the development of renewable energy technologies from underutilized wood waste, promoting sustainable energy solutions and environmental conservation.

1. Introduction

Biomass energy, in the form of briquettes, is the conversion of solid raw materials into a compacted form that is easily utilized. One of the materials used in briquettes is biomass waste. The by-product of the sawmill industry is biomass waste that accumulates and is not utilized (Damanik et al. 2023). The waste is in the form of pieces of wood, parts of branches and twigs, wood cutting and sawdust. According to Nasbey et al. (2022), biomass waste can be a type of waste generated by the cutting edge, machining, or processing of stems and shells, as well as harvesting waste such as stumps. Waste obtained from such plants and biomass leftovers can create environmental and health problems. Sawdust is a waste product generated by the wood processing industry that is not optimally utilized, posing a challenge to environmental safety as its improper disposal or burning is a source of pollution (Zbieć et al. 2022). It must be disposed of to prevent waste from accumulating. The purpose of this study is to dispose of the waste from sawmill industries by indirect wet processing of charcoal briquettes. Briquettes are a type of solid alternative energy resource that can help mitigate the growing problem of fossil fuel depletion. Bio-charcoal is a heavy, porous, and flammable substance produced when biomass feedstock is converted into charcoal via thermochemical processes while excluding air (Ghodake et al. 2021; Wijaya et al. 2025). It can be a good choice for charcoal production, given that firewood used for cooking is derived from waste produced by the wood processing industry (Antwi-Boasiako and Acheampong 2016).

Some other presentations of bio-charcoal briquettes, which are superior to ordinary charcoal, include longer combustion heat, lower smoke, various shapes and sizes, and the renewable use of raw materials, as well as being an alternative environmentally friendly source of energy (Kongprasert et al. 2019; Shiferaw et al. 2017; Suryaningsih and Nurhilal 2018). The use of bio-charcoal briquettes is inseparable from the quality of the product. Therefore, efforts to improve quality can be made using the carbonization method in briquetting. The carbonization method will create a product in the form of charcoal. Charcoal is the solid residue remaining after the decomposition of wood, which contains most of the carbon. To transform charcoal into briquettes, a densification process can be used. When the material is crushed into small pieces and then pressed, this method is used to compact biomass and increase its heating value (Rani et al. 2023; Vaish et al. 2022).

Bio-charcoal briquettes must meet standard calorific values to ensure optimal combustion performance as an alternative energy source. According to the Indonesian National Standard (SNI) 01-6235-2000, for instance, the minimum required calorific value of wood charcoal briquettes is ≥ 5,000 cal/g (BSN 2014). Additionally, previous research has recommended that high-quality bio-charcoal briquettes should have calorific values within the range of 4,500 to 7,000 cal/g, depending on the type of biomass (Akowuah et al. 2012). Consequently, a high calorific value is critically important in the production of bio-charcoal briquettes to ensure resource conversion efficiency and long-term sustainability. Although there is a bright prospect for the development of biomass energy, the quality as well as the conversion efficiency of bio-charcoal briquettes, are two major technical problems. The physical and chemical properties of briquettes, such as their density, fixed carbon content, volatile matter and ash content, will directly affect their combustion properties. Thus, low-density briquettes more easily catch fire and burn away, producing a lot of smoke and having a lower calorific value. On the other hand, high ash content results in low combustion efficiency (Shiferaw et al. 2017). Hence, the choice of processing techniques and adhesives will be critical factors in meeting each of these measurements.

The briquette process consists of two basic elements: raw materials and binders. The strength of the bond between the charcoal particles and the binder is one of the determinants of briquette quality. A contact between the two can be created by covering the pores and surfaces of the charcoal particles with adhesive, producing a charcoal-adhesive mixture (Ali et al. 2021; Zhang et al. 2018). Furthermore, pressure applied to these two combinations expands the area, and this expansion produces molecular forces that strengthen the bond in the briquettes. The glue is made from molasses, a by-product of the cane sugar industry. Furthermore, molasses has a high carbon density and low ember temperature, which results in a high rate of burning, thereby lowering the difficulty of igniting briquettes produced from molasses adhesive (Olugbade et al. 2019). Furthermore, combining materials like sawdust with a molasses binder can minimize the breaking or cracking of briquette products (Manyuchi et al. 2018). Pujiastuti et al. (2022) and Tanui et al. (2018) state that organic adhesives, such as molasses, are better than starch-based adhesives because the ash content of charcoal briquettes can be reduced. At a 10% concentration, molasses, a by-product of the sugar industry, has been proposed as a low-cost, environmentally friendly binder with the further advantage of improving combustion performance (Manyuchi et al. 2018).

A bonding agent is used to enhance the coherence of briquettes, thereby preventing what is commonly referred to as briquette breaks. A range of natural and synthetic adhesives, including starch, clay, and lignin-based adhesives, has been investigated. A cheaper and more environmentally friendly alternative to binders is molasses, a by-product of the sugar industry, which also improves combustion characteristics (Manyuchi et al. 2018). Although molasses is abundant and rich in carbon, its effects on the primary features of bio-charcoal briquettes have been studied to only a limited extent. Several studies comparing various types of adhesives have reported that molasses-based briquettes yield higher calorific values than other organic adhesives. For instance, the calorific value of cassava starch as an adhesive is between 4,500 and 5,100 cal/g (Gimba et al. 2022). However, values between 4,600 and 5,300 cal/g have been reported for tapioca starch-based briquettes (Pujiastuti et al. 2022). On the other hand, calorific values in the range of 5,200 cal/g to 5,500 cal/g of bio-charcoal briquettes bound with molasses have been reported to depend on the biomass composition and molasses concentration (Carnaje et al. 2018). The results indicate that molasses briquettes achieve calorific values that either meet or exceed the standard, making them a competitive and efficient biofuel product.

Various studies have investigated the effect of molasses as a binding agent for biomass briquette production and reported that it enhanced the briquette's physical properties (density, fixed carbon content, that is, heat content, mechanical strength, volatile matter) (Gimba et al. 2022; Manyuchi et al. 2018; Pujiastuti et al. 2020) Calorific values of molasses-bonded bio-charcoal briquettes were found to be above 5,200 cal/g and reached as high as 5,500 cal/g for different molasses proportions and biomass formulation (Carnaje et al. 2018). This value is higher than that of cassava starch-based briquettes (4,500 to 5,100 cal/g) (Gimba et al. 2022) and tapioca starch-based briquettes (4,600 to 5,300 cal/g) (Pujiastuti et al. 2022). Previous research has also shown that molasses-based briquettes have lower ash content and reduced volatile matter, thereby improving combustion efficiency (Shiferaw et al. 2017). Molasses have a high carbohydrate content, facilitating binding while contributing to higher energy output upon combustion (Nazari et al. 2020). Additionally, the molasses enhances the strength of the briquette by preventing it from cracking or losing shape during production and storage (Manyuchi et al. 2018). Nonetheless, there is a lack of experimental evidence on the possible influence of various molasses concentrations on bio-charcoal briquettes produced from sawdust. Moreover, no foundation analysis has been conducted regarding the necessary concentration of molasses that would balance both mechanical strength and combustion. Previous studies have primarily focused on the effect of molasses as an adhesive. However, insufficient research has been conducted on the impact of bio-charcoal on combustion efficiency and its physical integrity during combustion. Therefore, the present study aims to identify this gap by examining the properties of briquettes produced using different molasses concentrations.

This study investigates the physical and chemical properties of bio-charcoal briquettes made from sawdust waste with varying concentrations of molasses adhesives (5%, 10%, and 15%). The research is based on the hypothesis that increasing the molasses content will improve the density and fixed carbon while decreasing the volatile matter and ash content, thereby increasing the combustion efficiency. This research assumes that a higher concentration of molasses will increase density and fixed carbon but decrease volatile matter and ash content. Increasing the molasses concentration can improve the quality of combustion. The research aims to enhance briquette quality, combustion efficiency, and environmental sustainability by identifying the optimal molasses content. The proposed results will provide practical inspiration to bioenergy sites, which will have the possibility to produce high-performance, low-cost, and eco-friendly building and fuel briquettes at different scales.

2. Materials and Methods

2.1. Materials

The raw material for bio-charcoal briquettes consists of sawmill waste from a mixture of Teak (*Tectona grandis*), Sengon (*Albizia falcataria*), Kempas (*Koompassia malaccensis*) and Mahogany (*Swietenia mahagoni*) wood. The sawdust was obtained from UD Woods, a furniture manufacturing industry located in West Lombok Regency, West Nusa Tenggara. The collected sawdust was dried for five days until it reached a moisture content of 6–7%. A total of 20 kg of mixed sawdust was used in the production of charcoal. The adhesive used in briquette production is molasses (Molasses Tjap Bukit Mas, packaged by UD. Graha Tani), which can be used directly. Additionally, 1% potassium chlorate ($KClO_3$) was used as an oxidizer.

2.2. Bio-Charcoal Production

The wood charcoal was produced through a carbonization process using a modified drum kiln (**Fig. 1**). In this study, the sawdust used as a raw material was first carbonized, where the biomass was burned in a limited-oxygen environment using a simple drum kiln. This carbonization followed a modified method adapted from previous studies (Sotannde et al. 2010). Carbonization was carried out at a measured temperature range of 400–450°C for 4 hours or until the smoke emitted from the drum chimney turned thin and transparent, indicating the completion of the process. A thermogun is used to measure the temperature during the carbonization process. The drum kiln had a capacity of 10 kg, requiring two batches for the entire process. The charcoal produced from both batches was combined, and the yield was calculated.

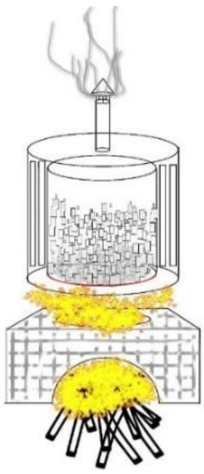

Fig. 1. Modified drum kiln.

2.3. Manufacture of Bio-Charcoal Briquettes

The charcoal was ground using a mortar (20 cm in diameter) and pestle, then sieved to obtain charcoal powder that passed through a 40-mesh sieve but was retained on a 60-mesh sieve. The bio-charcoal briquettes were prepared using a mixture of charcoal powder and molasses adhesive with three different ratios: 95%:5%, 90%:10%, and 85%:15%, along with an additional 1% potassium chlorate ($KClO_3$). Each variation was replicated three times, yielding a total of nine samples. A total of 80 g of well-mixed and smooth dough was placed into a mold (5 cm in diameter) and pressed using a hydraulic press (Hydraulic Jack Enerpack and Hand Pump Set) at 2.76 MPa. This bio-charcoal briquette manufacturing process followed a modified method adapted from previous studies (Haile et al. 2020). The finished bio-charcoal briquettes were then conditioned by storing them at room temperature for seven days (**Fig. 2**).

Fig. 2. The manufactured bio-charcoal briquettes.

2.4. Bio-Charcoal Briquette Testing

The characteristics of bio-charcoal briquettes include proximate analysis, which involves testing for density, moisture content, ash content, fly ash content, and calorific value. FTIR and SEM were used for analyzing the changes in functional groups and morphology of bio-charcoal briquettes. Each test was repeated three times for each treatment of the powder-to-adhesive ratio comparison. Proximate testing parameters, as outlined in SNI 01-6235-2003 standards, are presented in **Table 1**.

Table 1. Wood charcoal briquette quality requirement specification (BSN 2014)

No.	Parameter	Unit	SNI 01-6235-2003 Standard
1	Moisture content	%	≤ 8
2	Density	g/cm^3	0.44
3	Ash content	%	≤ 8
4	Volatile matter	%	≤ 15
5	Calorific value	cal/g	≤ 5000
6	Fixed carbon	%	≥ 77

2.4.1. Moisture content

A total of 2 g of bio-charcoal briquette pieces were oven-dried at 105°C for 24 hours in an electric oven (Memmert Model 100-800, Jerman). After that, the oven-dried weight was measured using an analytic balance (Ohaus Model PA 523, USA). The calculation of the moisture content followed the ASTM D-3173-03 standard as follows:

$$MC\ (\%) = \frac{a - b}{a} \times 100\% \quad (1)$$

where *MC* is moisture content, *a* is the initial weight (g), and *b* is the oven-dried weight (g).

2.4.2. Density

The density is obtained from the ratio between the briquette mass's weight and the whole briquette's volume. Weight was measured using analytical scales, and volume was calculated using digital calipers (Mitutoyo CD-15AX, Japan). The density standard refers to SNI 01-6235-2000. The density was calculated using Equation 2.

$$\rho\ (g/cm^3) = \frac{m}{v} \quad (2)$$

where ρ is the density of bio-charcoal briquettes (g/cm^3), *m* is the weight of bio-charcoal briquette (g), and *v* is the bio-charcoal briquette volume (cm^3).

2.4.3. Ash content determination

The calculation of ash content is based on the Indonesian National Standard (SNI) 01-6235-2000. Oven-dried test material of 1 g was weighed and placed in a porcelain crucible with a known weight. It was placed in an electric muffle furnace (JISICO, Model J-FM28, Korea) at 750ºC for 5 hours. After cooling in a desiccator, the sample was weighed until a constant weight was achieved. The ash content was calculated using Equation 3.

$$Ash\ content\ (\%) = \frac{ash\ weight}{initial\ weight} \times 100\% \quad (3)$$

2.4.4. Volatile matter

The volatile matter content was measured by first placing a 1 g sample in a porcelain crucible and then inserting it into an electric furnace (JISICO, Model J-FM28, Korea), which was preheated to 950 ± 20°C for 7 minutes. After heating, the sample was removed, stabilized, and weighed (Nasir 2015). The volatile matter content was calculated using Equation 4.

$$Volatile\ matter\ (\%) = \frac{b - c}{a} \times 100\% \quad (4)$$

where *c* is the mass of briquettes after heating at a temperature of 950°C (g).

2.4.5. Fixed carbon

The calculation of fixed carbon of bio-charcoal briquettes was obtained by measuring the reduction of the number 100 by the amount of volatile matter. The fixed carbon was calculated using Equation 5.

$$FC = 100 - (MC + VM + AC)\ \% \quad (5)$$

where *FC* is fixed carbon (%), *MC* is moisture content (%), *VM* is volatile matter (%), and *AC* is ash content (%).

2.4.6. Burning rate

The burning rate test aims to determine the duration of a fuel's flame. This testing process involves burning briquettes and then weighing the mass of the burned briquettes. The burning rate method proposed by (Okwu et al. 2018) was adopted. The burning rate was calculated using Equation 6.

$$\textit{Burning rate (\%)} = \frac{A}{B} \tag{6}$$

where A is the mass of fuel consumed (g), and B is the total time taken (minute).

2.4.7. Calorific value

The measurement of calorific value is conducted in accordance with SNI No. 01-6235-2000. The determination of calorific value using a bomb calorimeter (Cole Palmer Model IKA-C5003, USA) follows these steps: the bomb calorimeter is filled with water, with the volume depending on the size of the calorimeter used and the properties of the sample being tested. The initial temperature inside the calorimeter is recorded, and the sample is placed into the bomb calorimeter and sealed tightly. Ensure that all air is trapped inside the bomb. The sample is then burned, and the temperature increase is monitored within the calorimeter over a certain period. Afterward, the calorific value is calculated. The calorific value was calculated using Equation 7.

$$\textit{Calorific value (ca°C)} = \frac{(T2-T1) \times C}{m} \tag{7}$$

where $T1$ is the initial test temperature (°C), $T2$ is the final test temperature (°C), C is constant (2575.6 cal/°C), and m is sample mass (g).

2.5. Fourier Transform Infrared (FTIR) Analysis

FTIR analysis was performed using a Perkin Elmer Spectrum Two FTIR spectrometer. The sample was mixed with solid KBr as a dispersing agent in a ratio of 10–20:90−80. The mixture was finely ground, formed into a pellet, and placed in the sample holder for infrared spectrophotometric analysis. The infrared spectrum was recorded with a spectral resolution of 2 cm^{-1} at a temperature of 20°C, within the wavenumber range of 4,000–400 cm^{-1}.

2.6. Scanning Electron Microscope (SEM) Analysis

Surface morphology analysis of the bio-charcoal briquette was conducted using the *JEOL JCM-7000 NeoScope*™ on the charcoal powder to examine its surface structure and pore size. The process involved coating 60-mesh charcoal powder with platinum.

2.7. Data Analysis

Statistical analysis was conducted using R software 4.3.2 (Stowell 2014). To compare the mean values of each treatment in the powder-to-adhesive ratio comparison, the Tukey-Kramer test ($p < 0.05$) was employed.

3. Results and Discussion

3.1. Density

In general, the quality of bio-charcoal briquettes is determined based on physical properties, including density, moisture content, ash content, volatile matter content, bound carbon content, and calorific value. The quality standard for bio-charcoal briquettes refers to the Indonesian National Standard (SNI). Additionally, the shape and structure of the briquettes can be determined through scanning electron microscopy (SEM) and Fourier transform infrared spectroscopy (FTIR) analysis. The following are the results of the testing of sawdust bio-charcoal briquettes (**Table 2**).

Table 2. The test results of sawdust bio-charcoal briquettes

Adhesive content (%)	Component Testing					
	Density (g/cm^3)	Moisture content (%)	Ash content (%)	Volatile matter (%)	Fixed carbon (%)	Calorific value (cal/g)
5	0.76	4.28	6.57	47.09	42.06	5,222.5
10	0.77	4.32	6.45	38.44	50.79	5,420.0
15	0.85	5.03	6.25	32.20	56.52	5,215.5
SNI standard	0.44	≤ 8	≤ 8	≤ 15	≥ 77	$\geq 5{,}000$

Density affects the quality of charcoal briquettes, which is indicated by the ratio between the mass and volume of the briquette. Dense bio-charcoal briquettes will produce combustion and ignition for an extended period. This is due to the lack of voids in briquettes that have a high density. Briyartendra and Widayat (2019) stated that if the briquette has many voids, its high density will allow oxygen to penetrate more easily, causing it to burn more quickly and exhaust its fuel more rapidly. Increasing molasses binder up to 15% enhances briquette density by filling voids between charcoal particles, creating a more compact structure. However, molasses contains organic compounds that degrade during combustion, meaning that some energy is used to decompose the binder components before the heat can be generated. This reduces the overall calorific value of the briquette. Gimba et al. (2022) reported that although higher binder concentrations improve briquette density, they do not necessarily lead to higher energy output. Similarly, Oyelaran et al. (2015) found that low combustion rates can be associated with poor bonding, leading to higher porosity, increased oxidant infiltration, and causing the briquette to burn out more quickly.

Fig. 3 shows that the density value monotonically rises with increasing adhesive concentration. The effect is gradual, from low adhesive concentration to low density, as the adhesive fills the voids between charcoal particles, creating a more compact structure. This indicates that the binder forms strong interactions beyond surface adhesion. The density values of bio-charcoal briquettes at adhesive concentrations of 5%, 10%, and 15% were 0.76 g/cm^3, 0.77 g/cm^3, and 0.85 g/cm^3, respectively. This study shows that the higher the application of molasses adhesive, the higher the density of bio-charcoal briquettes. Gimba et al. (2022) reported that the density of briquettes increases with increasing adhesive concentration. This is attributed to the strong bonding capability of molasses at elevated concentrations, which allows it to blend more effectively with charcoal particles. According to Falemara et al. (2018), not only did briquettes made from molasses as an adhesive have a higher density than those made with starch or cassava flour (but also a small increase in carbide production); molasses worked better in filling the holes between particles of charcoal. With molasses, however, not only is a higher density possible, but also the increased number of filling points. Pujiastuti et al. (2022) also supported the findings of Falemara et al. (2018) in their study. Briquettes with a higher molasses content are thus denser and stronger than similar ones made with other natural adhesives. Molasses serve as an adhesive, causing the briquettes to have higher density. More fills in gaps around charcoal particles, resulting in a denser base. Charcoal briquettes made from bio-charcoal will have a significantly lower density than those made from other types. The process of carbonization or charring makes charcoal easily crumble; even the lightest puff of air aerates its small and thin particles.

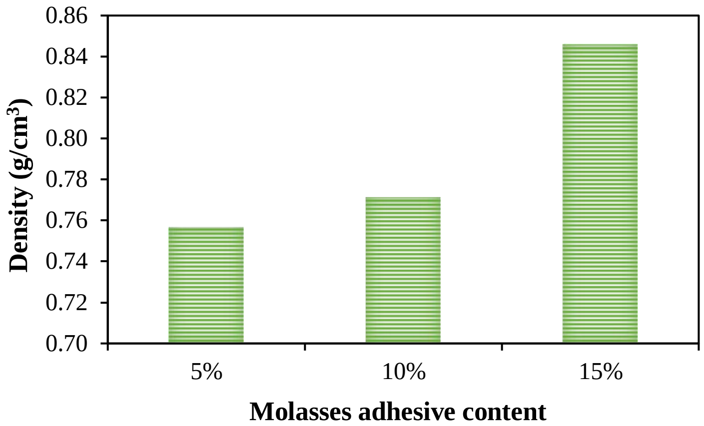

Fig. 3. The density value of sawdust bio-charcoal briquettes at various adhesive concentrations.

3.2. Moisture Content

The moisture content of charcoal briquettes is the ratio of the weight of water contained in them to the dry weight of the briquettes after baking. Charcoal briquettes have high hygroscopic properties. The high moisture content of bio-charcoal briquettes can inhibit ignition and reduce combustion temperatures (Mardan et al. 2019). They claim that the moisture content of briquettes affects the calorific value or the heat produced. The high calorific value can reduce the heating value because the heat stored in the briquette is first used to remove the existing heat before generating heat for combustion (Suttibak and Loengbudnark 2018). The presence of water on the surface of the briquette will evaporate immediately, while the water inside the briquette flows out through its pores and evaporates. The test results indicate that the moisture content of bio-charcoal briquettes with adhesive concentrations of 5%, 10%, and 15% is approximately 4.28%, 4.32%, and 5.03%, respectively. In contrast to the research of Pambudi et al. (2018), which showed that with an increase in density from 0.39 g/cm³ to 0.47 g/cm³, the water content decreased from 12.7% to 6.6%. However, in some cases, increased density can also be accompanied by higher moisture content, particularly when very fine charcoal particles are used.

Based on **Fig. 4**, a high moisture content is obtained in bio-charcoal briquettes with a 15% adhesive concentration. It is assumed that a large amount of molasses adhesive can affect the increase in water content in charcoal briquettes. Mordenti et al. (2021) reported that molasses consists of a carbohydrate content ranging from 48–53% and a water content ranging from 15–20%. Water in the raw materials affects the water content of the charcoal briquettes and the adhesive used (Shobar et al. 2020). Although molasses adhesives contain a significant amount of water, they are very important because they can be easily mixed with charcoal materials, provide good adhesion, and are easily dried into briquettes. The higher the adhesive concentration, the greater the briquette density, as the binder acts as a particle adhesive, filling the void spaces between charcoal particles. According to Suttibak and Loengbudnark (2018), an increase in adhesive content strengthens the briquette structure by reducing the size and number of open pores, resulting in a denser and more durable briquette. However, the hygroscopic properties of the binder also contribute to the briquette's moisture content, which may affect the combustion process. The moisture content of all charcoal briquette samples in this study falls within the maximum limit set by the Indonesian National Standard (SNI), which is 8%. Previous research by Suttibak and Loengbudnark (2018) and Sunardi et al. (2019) indicated that moisture content has a direct influence on both the fixed carbon levels and the overall combustion efficiency of briquettes. High moisture levels tend to reduce combustion performance, as a significant portion of the generated heat is first consumed to evaporate the water before actual burning can occur. Therefore, controlling moisture content is essential to ensure efficient energy output during briquette use.

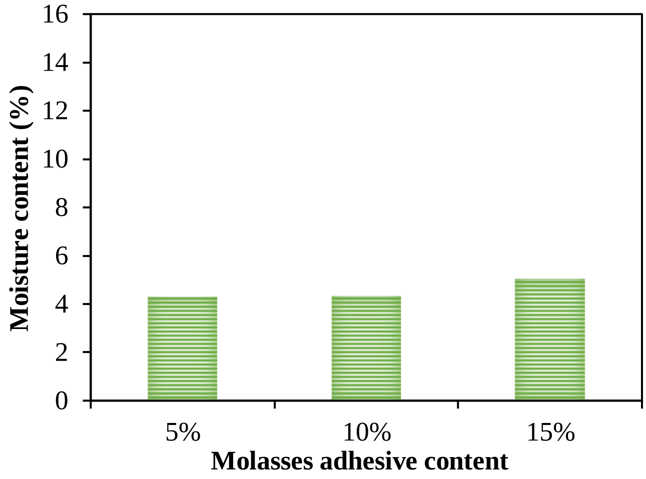

Fig. 4. The moisture content of sawdust bio-charcoal briquettes at various adhesive concentrations.

The type of adhesive used in bio-charcoal briquette production plays a significant role in determining both moisture content and calorific value. Hydrophobic adhesives, which naturally repel water, help lower the moisture content in briquettes. As a result, less energy is required to evaporate water during combustion, allowing for more efficient heat generation. On the other hand, adhesives that are hygroscopic or contain a high level of water can lead to increased moisture content, thereby reducing the overall calorific value, as a portion of the energy is diverted to evaporate the moisture. Comparative studies have shown that adhesive selection has a measurable impact on these properties. Harahap and Ginting (2024), for example, found that molasses-based briquettes retained more moisture than those made with tapioca starch. This difference is attributed to the naturally higher water content and liquid consistency of molasses compared to the more solid form of tapioca starch. In their findings, the highest moisture content (5.5634%) was recorded in briquettes composed of 80% bagasse and 20% sawdust using molasses as the binder. Conversely, the lowest moisture level (3.4213%) was observed in briquettes made from a 20:80 ratio and bound with 5% tapioca starch.

3.3. Ash Content

Ash content refers to the residue left behind after a briquette is burned to a constant weight. Ash content is directly proportional to the content of inorganic materials in the wood, serving as a suitable material for bio-charcoal briquettes. The primary component of ash is silica, which reduces the calorific value. The ash content in fuel does not significantly affect the combustion process, but it can make ignition more challenging. High ash content reduces calorific value (Sulistio et al. 2020). The ash content obtained in this study ranged from 6.57%, 6.45%, and 6.25% from each adhesive concentration of 5%, 10%, and 15%. Comparing these results with other studies using the same adhesive, a study by Harahap and Ginting (2024) found that bio-charcoal briquettes with molasses as an adhesive had an ash content of approximately 7.1%, slightly higher than those in this study but still within the acceptable range, that briquettes made with 10% molasses adhesive had an ash content of 6.8%, while those with 15% adhesive had 6.3%, further confirming the trend that higher adhesive concentrations can contribute to lower ash content. The results of this study indicate that the higher the concentration of adhesive in bio-charcoal briquettes, the lower the ash content.

In contrast, research by Falemara et al. (2018) and Yanti et al. (2023) revealed that the ash content of wood charcoal briquettes increased with the rise in adhesive concentration. A reduction in ash content has been observed in studies involving molasses as an adhesive. (Pujiastuti et al. 2022) reported that using molasses can effectively lower the ash content in charcoal briquettes. Supporting this finding, Muarif et al. (2024) noted that higher concentrations of adhesive tend to result in lower ash levels. (Dewi and Kholik 2020) also emphasized that the ash content is closely influenced by the type and quantity of adhesive used during briquette production.

Differences between measured calorific values and theoretical expectations can be attributed to several factors related to the physical and chemical properties of bio-charcoal briquettes. One of the main contributors is the influence of adhesive composition. While increasing adhesive concentration often improves density and reduces both ash and moisture content, some adhesives—such as molasses—contain organic substances that do not carbonize efficiently. Due to its high carbohydrate and water content, part of the energy during combustion is diverted to breaking down these adhesive components before generating usable heat (Mordenti et al. 2021). Moreover, higher adhesive levels can result in a denser briquette structure, which may restrict oxygen flow during combustion. This limitation in oxygen diffusion can hinder the oxidation process and ultimately reduce the briquette's overall calorific performance (Shobar et al. 2020). Changes in the chemical makeup of briquettes also play a role in influencing their calorific value. Suttibak and Loengbudnark (2018) observed that increasing the concentration of molasses as an adhesive tends to elevate the amount of volatile compounds rather than fixed carbon, which in turn leads to a lower calorific value. Since fixed carbon contributes more substantially to energy release during combustion, its proportion is critical. Another important factor is the moisture present in the adhesive. When adhesives contain high water content, a considerable portion of the energy is spent evaporating the moisture before full combustion can occur, thereby reducing the amount of heat available for energy generation (Pujiastuti et al. 2022). Additionally, chemical reactions that occur during combustion can impact overall efficiency. Some mineral components in the adhesive may form a crust on the briquette surface, inhibiting heat transfer and lowering combustion efficiency (Dewi and Kholik 2020). Although, in theory, increasing adhesive concentration should support calorific value improvement by enhancing density and reducing ash and moisture content, the findings of this study suggest that additional factors such as adhesive properties, volatile compound content, pore structure, and combustion efficiency play crucial roles in determining the final calorific value. Therefore, selecting the optimal type and amount of adhesive is crucial to enhance energy efficiency without significantly compromising the calorific value of the briquettes. Based on three variations of adhesive concentration, the ash content of bio-charcoal briquettes has met the SNI 01-6235-2000 standard, which is ≤ 8%.

3.4. Fixed Carbon

Fixed carbon is the carbon (C) bound in the bio-charcoal briquette in addition to the water, ash and volatile matter fractions. The lower the water content, ash content and volatile matter, the greater the carbon content. An inverse relationship exists between the water, ash, and volatile matter content of the briquettes and the fixed carbon they contain; generally, a higher content of these elements indicates a lower carbon content. As a result, there is a direct correlation between the fixed carbon levels in briquettes and their performance during combustion. In general, we can say that the higher the fixed carbon content, the longer the briquettes burn and the more rapidly they ignite. In other words, they are more efficient as a heating source (Hamid et al. 2016; Priyanto and Putri 2017). The levels of fixed carbon produced in this study ranged from 42.06% to 56.52% for each bio-charcoal briquette with adhesive concentrations of 5%, 10%, and 15%. These findings can also be compared with other studies that used molasses as an adhesive. A study by Chungcharoen and Srisang (2020) found that using molasses as an adhesive in agricultural waste-based bio-charcoal briquettes significantly increased fixed carbon content compared to other adhesives, such as tapioca flour or sago starch. Their study showed that molasses-based adhesives could yield up to 55% fixed carbon, which is close to the results in this study. Additionally, research by Obi et al. (2022) observed a similar trend, where briquettes with molasses adhesive exhibited higher fixed carbon content than those using lignin or starch-based adhesives.

Since fixed carbon contributes the most to combustion energy, it is surprising that the actual value of its proportion is different from the above explanation. This explanation can be made due to the peculiarities of combustion. The most probable reason is that volatile matter in this case prevails, and it cannot fully influence the combustion process. Although factors fixed carbon is responsible for sustaining combustion, it does not support the initial stage of ignition. Suttibak and Loengbudnark (2018) found that briquettes with high volatile matter tend to have low calorific value despite having relatively high fixed carbon. This trend can be explained by the fact that during combustion, volatile compounds quickly dissolve, preventing heat from being stored inside. If bio-charcoal briquettes have more volatile matter, some of the energy is used to evaporate parts of such matter to initiate combustion and cannot be passed on as heat. High fixed carbon in carbon-dominated bio-charcoal briquettes. This validates our previously reported work by Adeleke et al. (2021), which states that high-value fixed carbon indicates a high predominance of carbon in the product. The results revealed that the 5% adhesive content caused the lowest fixed carbon content in bio-charcoal briquettes. In comparison, the highest fixed carbon content was found in bio-charcoal briquettes with 15% adhesive content. A study by Obi et al. (2022) reported that the fixed carbon content of the briquettes increased while the ash content decreased, with an increase in molasses content as an adhesive. With the addition of adhesive, the value of fixed carbon is higher. That is due to the other organic materials in molasses adhesives, which increase its total carbon content. Carbonization, or initial combustion, will convert most of the organic matter in the molasses used as an adhesive into carbon. This means it will be able to enhance the fixed carbon in the briquettes. It can also enhance the amount of energy produced by combustion, making the combustion process more efficient. This fixed carbon is in the form of briquettes, as reported by Pujiastuti et al. (2022) and Putri et al. (2023). The results of this study show that all bio-charcoal briquettes with different adhesive concentrations have met the requirements of charcoal according to SNI 01-6235-2000, which is a minimum of 77%.

3.5. Volatile Matter

Volatile matter results from the devolatilization process, where the solid fuel undergoes decomposition characterized by the thermal rupture of chemical bonds and volatile matter is released from the briquette particles. Volatile substances consist of gases from combustible matter and gases from noncombustible matter and hydrocarbons. After combustion, combustible materials produce gases, including CO_2, SO_2, and water vapor, which exit as smoke or flue gas. In contrast, unburned materials produce gases, including O_2 and N_2, as smoke gas. This research resulted in volatile matter levels in bio-charcoal briquettes ranging from 47.09%, 38.44%, and 32.20% for each adhesive concentration of 5%, 10%, and 15%. The results showed that adding adhesive resulted in a low volatile matter content. A comparison with other studies using molasses as an adhesive shows a similar pattern regarding volatile matter content. These findings are also supported by Adeleke et al. (2021), who found that agricultural waste-based briquettes with molasses adhesive had a volatile matter content of approximately 40–50% at low adhesive concentrations but decreased to 28–35% at higher adhesive concentrations. When heated, molasses adhesive, which contains sugar and other organic materials, tends to evaporate as part of the volatile matter. During the combustion process, the material contained in the molasses will break down into volatile gases. The decrease in volatiles can be attributed to differences in the levels of cellulose and carbohydrates that are easily degraded during thermal treatment, as well as the percentage of water content (Nazari et al. 2020).

Another effect of lower volatile matter content at high adhesive concentrations is the higher water content compared to bio-charcoal briquettes with low adhesive concentrations. It is speculated that the high water content in the briquettes increases the energy requirements to evaporate water during the initial combustion process, resulting in lower initial combustion temperatures and preventing some components of the volatile matter from being fully released. However, this did not have a significant effect because the results of this study produced a high calorific value. The higher the volatile matter, the faster a fuel will burn and the more smoke it will make when the charcoal briquettes are ignited. Inegbedion and Ikpoza (2022) stated that high levels of volatile matter in a briquette indicate ease of ignition, rapid combustion, and a proportional increase in flame length but a low calorific value. The wood sawdust bio-charcoal briquettes produced have a percentage of volatile matter in the range of 10–25%, which is considered a good quality, as reported by Akintaro et al. (2017). This study did not meet the SNI 01-6235-2000 standard, which stipulates that the volatile matter for wood charcoal should be ≤ 15%. A higher volatile matter content does not necessarily indicate poor fuel quality. Adeleke et al. (2021) demonstrated that high-volatile fuels can also achieve the maximum heating value if they contain sufficient fixed carbon, as observed in this research (where the content of fixed carbon varied from 42.06% to 56.52%). Although the volatile matter content values obtained in this work do not match with the SNI standard of wood charcoal, this value relates to acceptable volatile matter content for biomass briquettes as indicated by previous works, where the briquette with higher volatile matter contents still can be applied for biomass briquette in particular due to some other factors such as ease of ignition, high fixed carbon contents, and the best burning efficiency.

3.6. Calorific Value

The calorific value is a crucial parameter that affects the burning power of charcoal briquettes. The higher the calorific value, the higher will be the combustibility of the briquettes. The calorific value of bio-charcoal briquettes produced from the research generated was as follows: 5,222.5 cal/g, 5,420 cal/g, and 5,215.1 cal/g at each adhesive concentration of 5%, 10%, and 15%, respectively. Under the SNI 01-6235-2000 wood charcoal briquette standard, the calorific value of the bio-charcoal briquettes was found to meet the standard. The high calorific value of charcoal briquettes, which provide sufficient heat, can meet the cooking needs of households and small-scale industries (Lubwama et al. 2020). Briquettes with the highest calorific value (10% self-adhesive bio-charcoal briquettes, 5,420 cal/g) and the lowest calorific value (15% self-adhesive biomass briquettes, 5,215.5 cal/g). The high calorific value of bio-charcoal briquettes is attributed to the high carbon content of the briquette material. Tanui et al. (2018) reported the calorific value for bio-char briquettes with 10% molasses adhesive to be in the range of 5400–5,500 cal/g. Similarly, Adeleke et al. (2021) Reported That Molasses-Based briquettes had a lower calorific value of 5,100–5,300 cal/g; however, varying compositions of raw materials can influence their calorimetry. The above comparisons show that the calorific values achieved were all within the expected range for molasses-bonded bio-charcoal briquettes; thus, the production of these briquettes is viable as an alternative fuel. Contrary to the high calorific value of biomass, its low calorific value is due to its low carbon content.

In addition, according to Hasan et al. (2017) and Widodo et al. (2021), the high calorific value of briquettes indicates that they are of high quality; the calorific value determines the heat energy produced. Besides, bio-charcoal briquettes are also influenced by the adhesive, such as molasses. The results of Carnaje et al. (2018) reveal a significant amount of carbon-based components in sugars that will impact the briquettes' proximate analysis and combustion properties. However, an optimal amount of adhesive can increase the calorific value due to its lower ash content (Shobar et al. 2020). Moreover, the characteristics of molasses are very sticky and are needed as a good material to bind and combine the briquettes. Furthermore, the application of potassium chlorate will also influence the calorific value. $KCLO_3$ is both an additive and an oxidizer, increasing the oxidation rate during combustion. As an oxidizer, it will provide additional oxygen during combustion, supporting the fuel's complete combustion and releasing more energy, thereby increasing the calorific value. Therefore, studies show that adding potassium chlorate will boost the calorific value of briquettes by about 5–10%. In particular, compared with the briquettes without the additive, the annealing calorific value increased by 5% to 10% (Ahmed et al. 2015)

3.7. Burning Rate

A high burning rate means it takes too long for the briquette to ash. The burning rate testing results for the burning rates in this study were 0.006 g/min, 0.007 g/min, and 0.010 g/min for adhesive concentrations of 5%, 10%, and 15%, respectively. 5% bio-charcoal briquettes have the lowest burning rate, and 15% bio-charcoal briquettes have the highest burning rate. The fact that bio-charcoal briquettes have low density influences the burning rate, as low density creates larger porosity. Teshome et al. (2024) conducted a prior investigation into the combustion rate, which was found to be between 0.005 g/min and 0.009 g/min, with varying concentrations of molasses used as an adhesive. Compared to our study value (0.007 g/min), the combustion rate for their 10% molasses briquette was lower (0.006 g/min). Additionally, Waluyo et al. (2023) used molasses as an adhesive and detected a 15% molasses briquette combustion rate, equivalent to a value of 0.009 g/min, which is lower than the 0.010 g/min detected in this study.

In this study, the calorific value increased at 10% molasses concentration (5,420 cal/g) but decreased at 15% (5,215.1 cal/g), while the combustion rate increased progressively from 0.006 g/min (5%) to 0.007 g/min (10%) and 0.010 g/min (15%). This inconsistency can be attributed to the variation in briquette density and porosity. When adhesive proportions are low, bio-charcoal briquettes become denser with more porosity and less densely bonded, allowing more oxygen to enter the briquette, which may result in faster burning but lower overall efficiency. The higher the percentage of the adhesive (10%) increased, the stronger the briquettes, the better the fuel retention, and the higher the heating value achieved. However, excessive adhesive content at a 15% molasses concentration caused the density of the briquettes to increase, resulting in faster burning but hampering oxygen permeation, thereby diminishing the combustion efficiency and calorific value. Adeleke et al. (2021) reported that a molasses adhesive content of 10% yielded a combustion rate of 0.0075 g/min for the bio-charcoal briquettes, similar to the one obtained in this work.

An earlier study by Hidayat et al. (2024), which utilized tapioca starch as a binding agent, demonstrated that the combustion rate (0.004–0.008 g/min) was generally lower. This supports the suggestion that relative to starch-based glue, increasing the combustion intensity in molasses adhesive is beneficial. It is important to note that high molasses levels do not necessarily raise energy efficiency. They can bring fast surface ignition but poor energy output, which would explain why the calorific value is lowered at a 15% molasses concentration despite a higher combustion rate. This is only logical, given the conditions it creates. Therefore, with a balance of combustion rate, density, and calorific value, 10% molasses seems to be the best concentration. Efficient energy release is ensured while steady combustion is maintained at rest.

The comparison concludes that the experimental results in the current research are similar to the literature, indicating that increasing the adhesive concentration affects the combustion rate of bio-charcoal briquettes. Oyelaran et al. (2015) found that at low burn rates, poor bonding likely resulted in higher porosity, which in turn led to increased oxidant infiltration and faster combustion. Bio-charcoal briquettes with high density typically contain more fuel per volume, allowing combustion to last longer and be more stable. However, very high density can slow the entry of oxygen into the briquettes' pores, reducing the burning rate and causing less efficient combustion. Additionally, the addition of potassium chlorate affects the ignition of bio-charcoal briquettes. Potassium chlorate is an oxidizing agent often added to briquettes to accelerate the burning rate. Potassium chlorate increases the oxygen supply during combustion, accelerating the combustion reaction and increasing the combustion temperature. The results of this study produce a fairly long burning rate.

3.8. Scanning Electron Microscope (SEM) Analysis

SEM is a characterization instrument used to test the microstructure of a sample. SEM testing (**Fig. 5**) reveals the surface morphology of bio-charcoal briquettes using a 15% molasses adhesive at 2000x magnification and a 60-mesh particle size. The surface morphology of the briquettes is characterized by a hollow structure, blending into each other with an irregular shape but featuring flat pores and cavities. The cavity in the center of the briquette increases the surface area, thereby enhancing the combustion rate. The observation that pores appear predominantly in the center of the bio-charcoal briquette in the SEM image is likely due to the non-uniform mixing of the materials, particularly the distribution of $KClO_3$ as an oxidizing agent. $KClO_3$ has a higher density than the main components, such as charcoal powder and molasses, which may cause it to settle toward the center or bottom of the mixture during the molding process, especially if not thoroughly mixed for a sufficient duration.

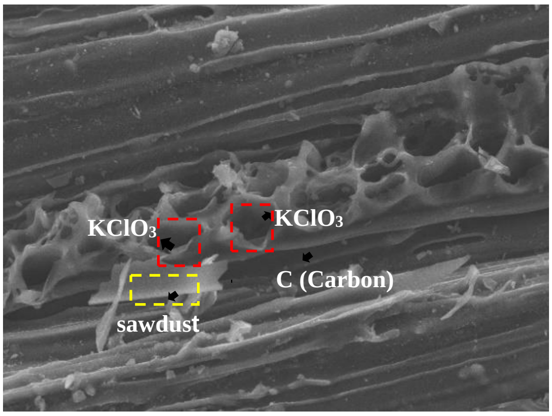

Fig. 5. SEM results on sawdust bio-charcoal briquettes.

The presence of voids in the center may result from thermal decomposition or gas release from $KClO_3$ during combustion, which tends to accumulate in areas with higher concentrations of the oxidizing agent. $KClO_3$ is known to enhance oxygen release and accelerate combustion, and the gas formation in concentrated zones can lead to the formation of pores in localized regions such as the center (Carnaje et al. 2018) argue that a good pore structure of briquettes can help improve the efficiency of charcoal combustion due to the availability of a lot of airflows, allowing oxygen and air to circulate in bio-charcoal briquettes. Additionally, adhesives can provide surface bonding of particles, resulting in strong bonds (Nasbey et al. 2022). Based on these conditions, the briquettes will burn easily and produce high calorific value. SEM analysis can demonstrate the components of bio-charcoal briquettes in the form of elements, as shown in **Fig. 5**. Meanwhile, the element graphs of each component of the bio-charcoal briquette are shown in **Fig. 6**.

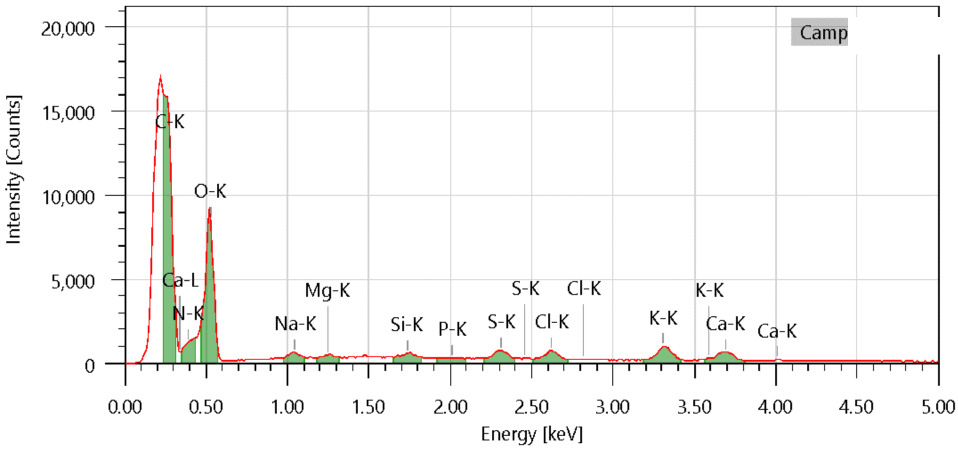

Fig. 6. SEM analysis element chart.

Based on **Table 3**, the SEM test results of the bio-charcoal briquettes show that they contain 11. These components include carbon, oxygen, sodium, magnesium, silicon, phosphorous, sulphur, chlorine, and calcium. Potassium was detected as the main element derived from potassium chlorate. Chlorine and potassium were detected, confirming the presence of potassium chlorate in the briquettes. Oxygen would also appear in significant amounts due to the presence of cellulose and lignin in the wood and oxygen-containing potassium chlorate. There are also other elements, such as calcium (Ca), magnesium (Mg), and silicon (Si), present in small amounts, which originate from natural impurities in the wood. Still, they will be in much lower concentrations than carbon, oxygen, potassium, and chlorine. Carbon was identified as the dominant component in bio-charcoal briquettes. This is one reason why briquettes made from sawmill waste can be used as an alternative fuel.

Table 3. Element composition of sawdust bio-composite briquettes

Element	Mass%	Atom%
C	51.74±0.64	48.86±0.61
N	13.41±0.49	14.46±0.52
O	26.08±0.22	32.81±0.28
Na	0.90±0.06	0.59±0.04
Mg	0.32±0.03	0.20±0.02
Si	0.30±0.03	0.16±0.02
P	0.09±0.02	0.05±0.01
S	1.05±0.05	0.50±0.02
Cl	1.20±0.05	0.51±0.02
K	2.74±0.09	1.06±0.04
Ca	2.16±0.09	0.82±0.03
Total	**100.00**	**100.00**

3.9. Fourier Transform Infrared (FTIR) Analysis

To determine the functional groups present in the charcoal resulting from carbonization using a drum kiln reactor, identification is carried out using Fourier Transform Infrared Spectroscopy (FTIR). **Fig. 7** shows strong absorption in the area of wave numbers 3,000–3,400 cm^{-1} (indicating there are OH functional groups), 2,860–2,970 cm^{-1} (indicating there are C-H functional groups), 1,510–1,560 cm^{-1} (indicating there are C=O functional groups) and 1,050 (indicating there are C-O-H functional groups). These results demonstrate that many functional groups are still present in sawdust. **Fig. 8** displays several peaks in all samples of bio-charcoal briquettes, such as at wave numbers 3,400 cm^{-1}, 2,931 cm^{-1}, and 1,050 cm^{-1}. The complete interpretation is presented in **Table 4**.

At 5% molasses concentration, the FTIR spectrum shows lower peak intensities. This means that the number of functional groups from molasses, such as hydroxyl (-OH), carbonyl (C=O), and C-H groups, are relatively few in this sample. The main peaks may occur around 3,400 cm^{-1} (O-H stretching), 2,931 cm^{-1} (C-H stretching), and 1,050 cm^{-1} (C=O stretching). The peaks on the FTIR spectra increase in intensity as the molasses composition reaches 10%, indicating that more functional groups are involved in the chemical structure of the briquettes. The bands at approximately 3,400 cm^{-1}, 2,931 cm^{-1}, and 1,050 cm^{-1} are more intense, suggesting high intensities for the O-H, C-H, and C=O vibrations (Harussani et al. 2021). The FTIR spectrum exhibited higher peaks at a 15% concentration, particularly in regions associated with the hydroxy and carbonyl group vibrations. The increased intensity peaks at approximately 3,400 cm^{-1} and 1,057 cm^{-1} may be attributed to the high presence of molasses, resulting in a high interaction between the functional groups of molasses and the wood powder that forms the briquettes (Obi et al., 2022). The active sites of the functional groups in molasses and sawdust briquettes indicate that molasses, containing hydroxyl (-OH) and carbonyl (C=O) groups, can form hydrogen bonds or ester bonds with the functional units of sawdust in the matrix. Sawdust with a higher wheat straw-to-molasses ratio in briquettes was densified and exhibited stronger inter-particle interaction, as revealed by the higher peak intensity of the FTIR spectrum. It can also strengthen the briquette structure and affect the burning of the briquettes (Nasbey et al. 2022). A high concentration of adhesive may lead to low residue formation, which can affect the energy efficiency of the briquettes.

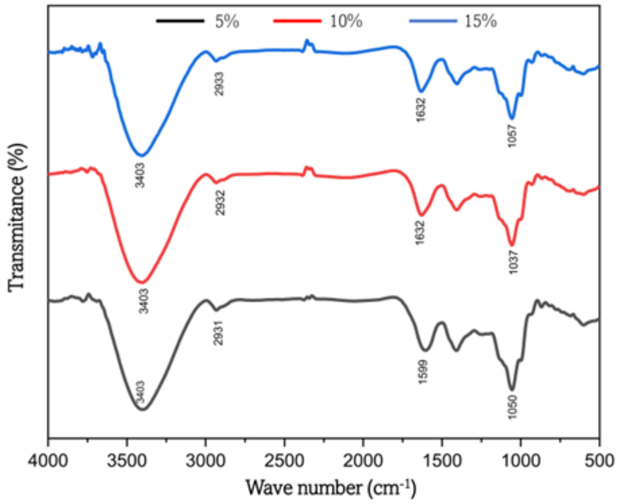

Fig. 7. FTIR spectra of sawdust bio-charcoal briquettes at varying concentrations of molasses adhesive.

Table 4. Recapitulation of FTIR wave peaks found in bio-charcoal briquettes and their interpretation

Wave number (cm^{-1})	Peak interpretation	Structural polymer	Reference
3,400	OH stretching	Lignocellulosic polymer (cellulose and hemicellulose)	(Lisperguer et al. 2009)
2,931	C-H stretching	Carbosillic acid	(Pandey 1999)
1,050	C=O stretching + ester bond	Lignin	(Pandey 1999)

4. Conclusions

Bio-charcoal briquettes made from sawdust waste with varying concentrations of molasses adhesive exhibit distinct physical and chemical properties. ash content of 6.45%, volatile matter of 38.44%, fixed carbon of 50.79%, and the highest calorific value of 5,420 cal/g. The balance between high fixed carbon and lower volatile matter contributed to energy efficiency and stable combustion. However, when the molasses concentration was increased to 15%, the calorific value decreased to 5,215.5 cal/g, despite an increase in fixed carbon to 56.52% and a decrease in volatile matter to 32.2%. This decline in calorific value is likely due to excessive density (0.85 g/cm^3), which restricts oxygen diffusion during combustion and hampers optimal energy release. Scanning

Electron Microscopy (SEM) and Fourier Transform Infrared (FTIR) analyses revealed that increasing the adhesive concentration improved porosity and chemical bonding, thereby enhancing combustion efficiency. The addition of potassium chlorate has a significant influence on the calorific value of bio-charcoal briquettes. Potassium chlorate acts as an additive and oxidizer, enhancing oxidation during the combustion process. By providing additional oxygen, potassium chlorate facilitates more efficient fuel combustion, resulting in a higher calorific value as more energy is released and establishing these briquettes as a viable, eco-friendly alternative fuel source.

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Author Contributions

A.C.I.: Conceptualization, Methodology, Software, and Validation; R.V.N.: Formal Analysis, Investigation, Resources, Data Curation, and Writing – Original Draft Preparation; D.S.R.: Writing – Review and Editing, Visualization, Supervision, Project Administration, Funding Acquisition; K.W.: Writing – Review and Editing, Visualization, Supervision, Project Administration, Funding Acquisition.

Conflict of Interest

The authors declare no conflict of interest.

Declaration of Generative AI and AI-Assisted Technologies in the Manuscript Preparation

During the preparation of this work, the authors utilized ChatGPT (OpenAI) to assist with language refinement and improve sentence clarity. After using this tool, the authors reviewed and edited the content as necessary and took full responsibility for the publication's content.

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