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Effect of Carbonization Temperature, Particle Size, and Binder Type on the Quality and CO Emissions of Oil Palm Shell Bio-Briquettes

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ABSTRACT

Bio briquettes from palm kernel shells have the potential to replace fossil fuels as an alternative energy source. However, their quality is largely determined by the characteristics of the raw materials and the type of binder. This study aims to analyze the effect of binder type (starch and molasses), carbonization temperature, charcoal particle size, and binder concentration on briquette quality. The parameters tested included moisture content, ash content, compressive strength, calorific value, and CO_2 emissions, as specified in the Indonesian National Standard (SNI). Briquettes were produced through carbonization, mixing, molding, and drying, then tested by proximate analysis, compression testing, calorimetry, and gas emissions analysis. The results indicated that binder type affects moisture content, ash content, and strength, but does not impact calorific value. Briquettes with molasses produced the lowest moisture content of 1.1%, namely in samples with 350°C, 100 mesh, 20% molasses. The lowest ash content and highest sample strength were obtained in samples with starch binder (350°C, 60 mesh, 20% starch), namely 2.2% and 39.91 Kg/cm^2. The sample with the highest calorific value was 6561.49 Cal/g (400°C, 60 mesh, 20% molasses). Interestingly, the binder type did not significantly affect the calorific value; particle size was the dominant factor. In terms of emissions, molasses produced lower CO_2 (812 ppm) than starch, at 400°C, 60 mesh particles, and a molasses concentration of 15%. This study confirms that the choice of binder significantly influences the physical and mechanical properties of bio briquettes, but does not significantly affect their calorific value. These findings provide important guidance for optimizing palm oil waste-based briquette formulations to produce efficient, environmentally friendly, renewable energy.

Keyword: *briquettes, oil palm shell, renewable energy, carbon monoxide, molasses*

ABSTRAK

Briket bio dari cangkang inti sawit berpotensi menggantikan bahan bakar fosil sebagai sumber energi alternatif. Namun, kualitasnya sebagian besar ditentukan oleh karakteristik bahan baku dan jenis pengikat. Studi ini bertujuan untuk menganalisis pengaruh jenis pengikat (pati dan molase), suhu karbonisasi, ukuran partikel arang, dan konsentrasi pengikat terhadap kualitas briket. Parameter yang diuji meliputi kadar air, kadar abu, kekuatan tekan, nilai kalor, dan emisi CO_2, sebagaimana ditentukan dalam Standar Nasional Indonesia (SNI). Briket diproduksi melalui proses karbonisasi, pencampuran, pencetakan, dan pengeringan, kemudian diuji dengan analisis proksimat, uji tekan, kalorimetri, dan analisis emisi gas. Hasil penelitian menunjukkan bahwa jenis pengikat memengaruhi kadar air, kadar abu, dan kekuatan, tetapi tidak memengaruhi nilai kalor. Briket dengan molase menghasilkan kadar air terendah sebesar 1,1%, yaitu pada sampel dengan

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suhu 350°C, ukuran arang 100 mesh, dan konsentrasi molase 20%. Kadar abu terendah dan kekuatan sampel tertinggi diperoleh pada sampel dengan pengikat pati (350°C, 60 mesh, 20% pati), yaitu 2,2% dan 39,91 Kg/cm^2. Sampel dengan nilai kalor tertinggi adalah 6561,49 Kal/g (400°C, 60 mesh, 20% molase). Menariknya, jenis pengikat tidak secara signifikan memengaruhi nilai kalor; ukuran partikel merupakan faktor dominan. Dari segi emisi, molase menghasilkan CO2 yang lebih rendah (812 ppm) daripada pati, pada suhu 400°C, partikel 60 mesh, dan konsentrasi molase 15%. Studi ini menegaskan bahwa pemilihan pengikat secara signifikan memengaruhi sifat fisik dan mekanik briket bio, tetapi tidak secara signifikan memengaruhi nilai kalornya. Temuan ini memberikan panduan penting untuk mengoptimalkan formulasi briket berbasis limbah minyak sawit untuk menghasilkan energi terbarukan yang efisien dan ramah lingkungan..

Kata kunci: Briket, kelapa sawit, energy terbarukan, karbon monoksida, molase

1. Introduction

Oil palm is a plantation crop that produces a substantial portion of the world's vegetable oil compared to other plantation crops. The processing of this plant not only yields oil but also generates a significant amount of waste. Solid palm oil waste consists of empty fruit bunches (EFB), palm kernel shells, and mesocarp fiber. The processing of 1 (one) ton of fresh fruit bunches (FFB) yields 130 kg of fiber waste and 6.5%, or 65 kg, of palm kernel shell waste [1]. Palm kernel shells contain lignocellulose with high carbon content and possess a higher density than wood, making them highly suitable for charcoal production [2]. The compaction of lingo cellulosic waste enhances the energy utilization of biomass when used as fuel for power generation [3]. Furthermore, shell waste has significant energy content, positioning it as a potential renewable energy source [4][5].

Energy is vital for economic activities, residences, industry, commerce, and transportation. The majority of Indonesia's energy supply is derived from fossil fuels, which are non-renewable resources. Energy demand is projected to continuously increase, while the reserves of petroleum and coal are dwindling. Moreover, the use of fossil fuels for energy contributes to excess carbon in the atmosphere, leading to global warming. Ensuring access to affordable, reliable, sustainable, and modern energy is one of the 2030 Sustainable Development Goals, making energy sustainability a global issue that requires commitment from both central and local governments. In Indonesia, the policy on new and renewable energy is outlined in Government Regulation No. 79 of 2014 concerning the National Energy Policy (KEN). This document sets targets for new and renewable energy to reach 23% by 2025 and a minimum of 31% by 2050. Conversely, dependence on petroleum and coal is targeted to decrease to 20% and 25%, respectively. The increase in renewable energy use is pursued through the utilization of organic-based waste. The high consumption of coal in Steam Power Plants (PLTU) has prompted the government to issue Minister of Energy and Mineral Resources Regulation No. 12 of 2023 concerning the utilization of biomass fuel as a co-firing fuel in PLTUs. The abundant availability of palm kernel shell raw materials on the island of Sumatra makes palm shells one of the most potential organic fuels to be developed as a co-firing biomass fuel in PLTUs. Biomass co-firing involves the simultaneous combustion of coal with one or more biomass fuels in a specific ratio to partially substitute coal while considering fuel quality. The use of palm kernel shells for co-firing has been trialed in several PLTUs. However, the lower calorific value of palm shells compared to coal limits this substitution to small quantities. Therefore, efforts are needed to enhance the calorific value of palm shells by processing them into palm shell bio-briquettes.

Bio-briquettes consist of powdered charcoal combined with a binder, shaped into defined forms, and subsequently solidified through a pressing process for use as fuel. The quality of wood-based charcoal briquettes is influenced by factors such as moisture content, volatile matter, ash content, and calorific value. Moreover, bio-briquettes are anticipated to produce minimal CO2 emissions during combustion. Briquettes produced from agricultural waste provide the benefit of transforming biomass, characterized by low density, low calorific value, and high moisture content in its raw state, into an efficient briquette fuel [4].

The production of briquettes from organic materials has utilized various types of organic waste, such as coconut shells, candlenut wood waste, and corn cobs [6][7]. Currently, briquette production often focuses solely on the heat energy generated without assessing the emissions produced from the combustion process[8][9][10][11][12]. However, the emergence of organic-based alternative energy sources is expected to reduce greenhouse gas emissions, a pressing global issue, and decrease dependence on non-renewable energy sources. Therefore, this research aims to produce briquettes that not only have a high calorific value but also low gas emissions. This study selects Carbon Monoxide (CO) as a key emission parameter, as it acts as a precursor to greenhouse gases like CO_2 [13]. Furthermore, CO has a direct negative impact on health due to its ability to bind with hemoglobin in the blood; high concentrations of CO can be fatal [14].

This research aims to produce high-quality palm shell charcoal bio-briquettes with a high calorific value and low CO emissions, enabling their use as biomass co-firing in PLTU combustion processes at a higher percentage than raw palm shells or empty fruit bunches (EFB). This study employs variations in carbonization temperature, charcoal particle size, and the concentration and type of binder (namely starch and molasses) in the bio-briquette production. This research is crucial to ensure that the management of plantation waste into a renewable energy source focuses not only on product quality but also on the resulting environmental quality.

2. Methods

This research utilized an experimental approach, incorporating palm kernel shell raw material sourced from PTPN IV along with binders such as molasses and starch. The research design is described as follows:

Table 1. Temperature variation, particle sizes, and binder concentration in briquettes

Sample Code	Burn temperature (^{0}C)	Particels size (mesh)	Binder Concentration* (g)
1	300	60	4.5
2	300	60	6
3	300	60	7.5
4	300	80	4.5
5	300	80	6
6	300	80	7.5
7	300	100	4.5
8	300	100	6
9	300	100	7.5
10	350	60	4.5
11	350	60	6
12	350	60	7.5
13	350	80	4.5
14	350	80	6
15	350	80	7.5
16	350	100	4.5
17	350	100	6
18	350	100	7.5
19	400	60	4.5
20	400	60	6
21	400	60	7.5
22	400	80	4.5
23	400	80	6
24	400	80	7.5
25	400	100	4.5
26	400	100	6
27	400	100	7.5

**The binder in this research are molasses and starch*

The bio-briquette production process comprised multiple stages: the generation of palm kernel shell charcoal, binder preparation, charcoal and binder amalgamation, briquette molding, drying, and concluding with quality assessment, which encompassed moisture content analysis, ash content evaluation, compressive strength measurement, calorific value determination, and CO emissions testing. The palm kernel shells were sun-dried for three days or until thoroughly desiccated. The desiccated shells were subsequently positioned in a Faithfull brand furnace and subjected to carbonization at temperatures of 300 °C, 350 °C, and 400 °C, as detailed in Table 1. The carbonization process in the furnace was sustained for two hours. The resultant charcoal was preserved in a desiccator for 24 hours and then ground using a disk mill. The powdered charcoal was further sieved to designated particle sizes utilizing meshes of 60, 80, and 100, as outlined in Table 1. The starch binder was created by combining distilled water with pre-measured starch powder in a 1:4 (w/v) ratio. The mixture was heated to 70 °C while being stirred continually until it thickened and became translucent. The molasses binder, a by-product of sugar cane processing, was measured according to the concentrations outlined in Table 1. Thereafter, 30 g of ground palm kernel shell charcoal, possessing the specified particle size, was combined with the binder according to the formulae outlined in Table 1. The charcoal-binder mixture is manually shaped into a cube using a mold measuring 3 cm by 3 cm by 3 cm, as illustrated in Figure 1.

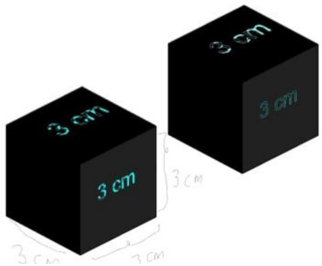

Figure 1. Visual of Briquette

The molded briquettes were sun-dried for three days under direct sunlight. Subsequently, the briquettes were packaged and stored in airtight containers equipped with silica gel to maintain a low moisture content. The quality testing of the briquettes encompassed moisture content, ash content, compressive strength, calorific value, and CO emissions. The moisture content and ash content tests were conducted in accordance with the Indonesian National Standard (SNI) with number 1683:2021 for wood charcoal briquettes. Briquettes weighed before dried in oven and then reweighed after briquetted were placed in an oven at 105oC for 4 hours. The moisture content value in the sample is the difference between the sample's weight before and after oven-drying. For analysis ash content, sample was placed in furnace at a temperature 800oC for 2 hours. The compressive strength of the palm shell bio-briquettes was tested following SNI with number 03-0691-1989 using a Universal Testing Machine. The calorific value was determined according to SNI 1683:2021 using a bomb calorimeter. The briquette combustion emission test method adhered to SNI 19-7117.10-2005 and used a gas analyzer. For the emission test, the briquettes were combusted using a dedicated briquette stove, as illustrated in the following figure:

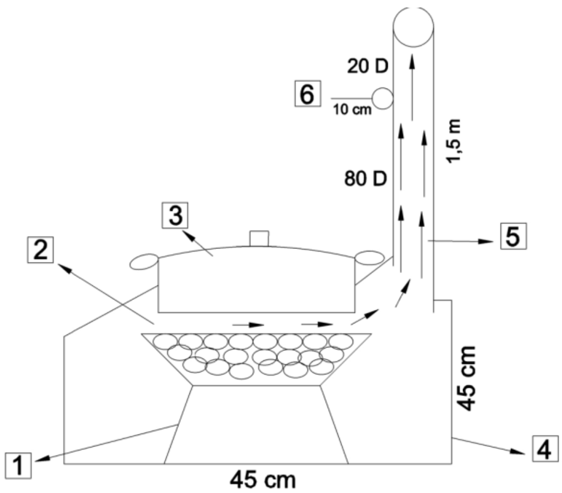

Figure 2. Briquette Stove

The briquette stove comprises six primary components: the furnace body (1), combustion chamber (2), pot (3), furnace insulating wall (4), chimney (5), and sampling port (6). Sampling of CO emissions from the chimney in the briquette stove refers to the National Indonesian Standard with number 7117.13.2009.

Each briquette mixture sample was treated as an individual replicate. All statistical analyses were performed using IBM SPSS Statistics (version 26.0). Prior to inferential testing, the normality of data distribution for each proximate parameter was assessed using the Kolmogorov–Smirnov test. Results indicated that all variables were normally distributed ($p < 0.05$), confirming the appropriateness of parametric statistical methods for subsequent analyses. To evaluate differences in proximate result between briquettes produced using two types of binders, an independent samples t-test was conducted for each parameter. This test was selected based on the fulfillment of normality assumptions and the independent nature of the two experimental groups. Statistical significance was determined at a confidence level of 95% ($\alpha = 0.05$). A p-value of less than 0.05 was considered indicative of a statistically significant difference between the two binder treatments for a given parameter.

3. Results and Discussion

1.1 Moisture content (%)

Moisture content is a critical quality parameter determining the overall quality of briquettes. High-quality briquettes possess low moisture content. The Indonesian National Standard (SNI) 01-6235-2000 for wood charcoal briquettes stipulates a moisture content of ≤ 8%. Moisture content is intrinsically linked to the calorific value of a briquette. A high moisture level reduces the effective calorific value, as a portion of the energy released during combustion is expended on vaporizing the water [15]. The moisture content values of the palm kernel shell briquettes, with variations in temperature, mesh size, binder type, and concentration, are presented in Figure 3 below.

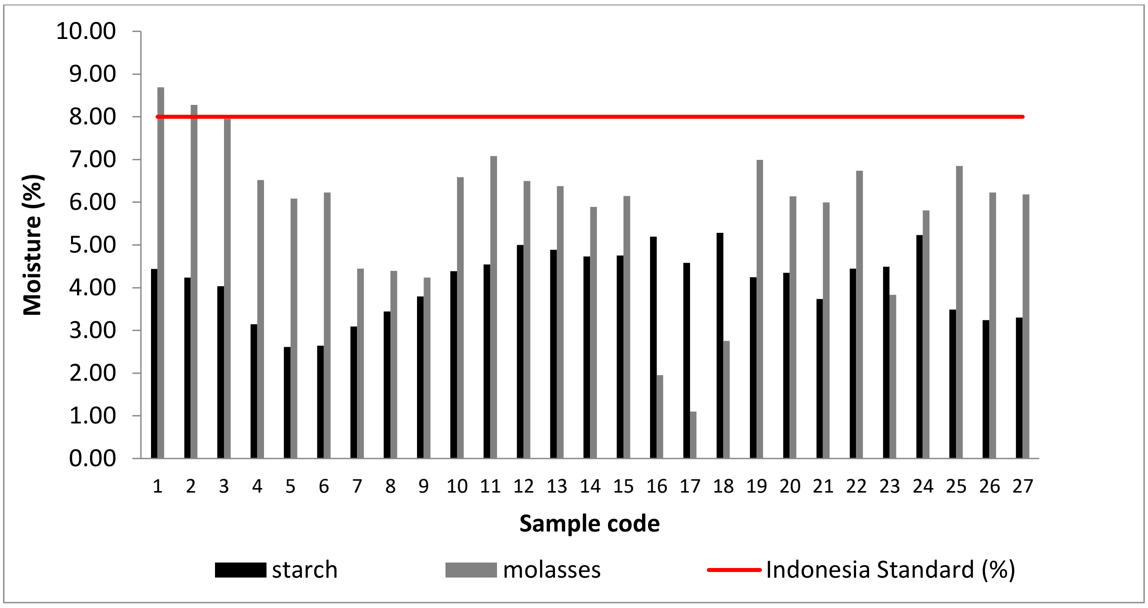

Figure 3. Moisture content of Bio-briquette

The data presented above indicate that nearly all briquettes, across variations in temperature, mesh size, binder type, and concentration, exhibited moisture content below 8%. This confirms their compliance with the quality standard stipulated in SNI 01-6235-2000, which mandates a moisture content of ≤ 8%. Briquette sample 17 (350°C, 100 mesh, 20% molasses) had the lowest moisture content of 1.1%. However, briquettes with codes 1 and 2, which utilized molasses as a binder, recorded moisture levels exceeding 8%, thus failing to meet the SNI standard. These were the briquettes carbonized at 300°C with molasses binder at concentrations of 15% and 20%. The independent t-test at the 95% confidence level found a significant difference in moisture content between samples with different types of binder ($p = 0.000$). This indicates that the binder type affects the moisture content of the briquettes.

The inverse relationship between carbonization temperature and moisture content can be attributed to the reduced number of pores trapping air and water at higher temperatures, leading to a drier final product [16]. Furthermore, the inherently hygroscopic nature of molasses is a significant contributing factor. Molasses consists primarily of carbohydrates and water, with sucrose and reducing sugars comprising 40%-60% (w/w) and its own moisture content being below 20% (w/w). This composition is suspected to introduce additional moisture into the briquette matrix [17]. The quantity of binder used also influences moisture content; a higher binder concentration generally leads to a corresponding increase in the briquette's final moisture level. From a practical standpoint, low moisture content is highly desirable. It reduces the energy required for drying, enhances combustion efficiency, and lowers the carbon footprint associated with production [18]. Additionally, low moisture content is advantageous for the storage and transportation of the final product, preventing degradation and maintaining quality[19].

3.2. Ash Content

Ash content is an indicator of the amount of inorganic residue remaining after the complete combustion of a fuel. It represents the products of incomplete combustion, which consist largely of mineral matter but may also contain some unburned carbon or other oxidized residues[20]. A high-quality briquette should possess low ash content. According to the Indonesian National Standard (SNI) 01-6235-2000, the acceptable ash content for charcoal briquettes is ≤ 8%. The presence of ash can interfere with the combustion process and potentially cause corrosion. High ash content leads to the formation of mineral deposits or slag during combustion, which fouls the furnace, induces corrosion, and ultimately degrades combustion quality[1]. The results of the ash content measurement for the palm kernel shell briquettes using starch and molasses binders are presented in the following figure 4:

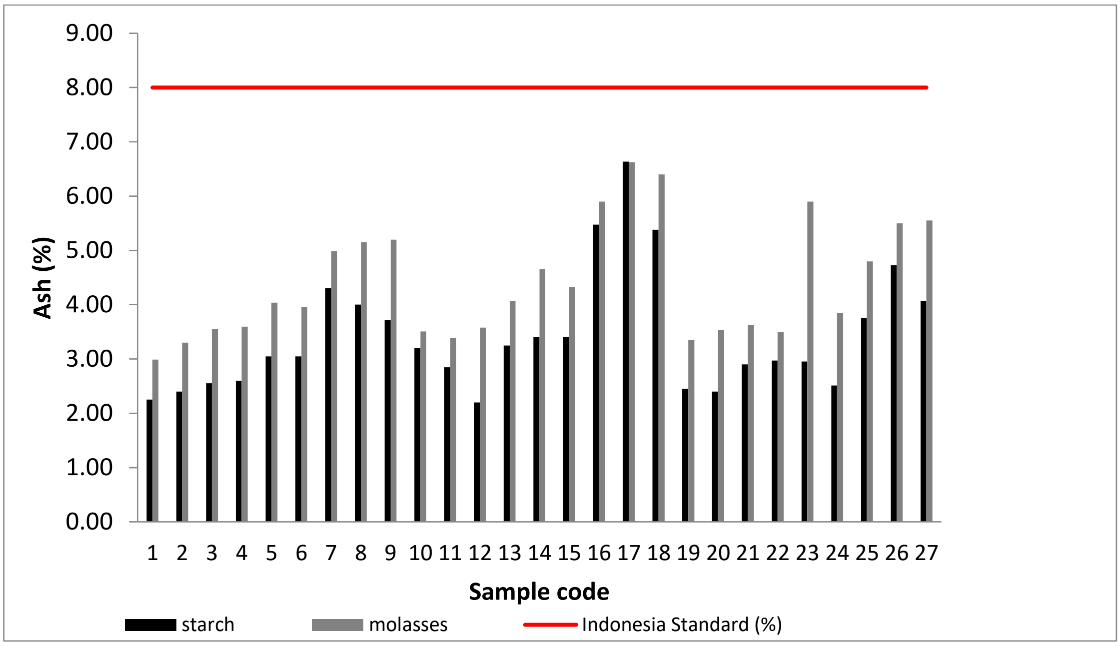

Figure 4. Levels of ash Bio-briquette

The analysis of the ash content from the combustion of the palm kernel shell briquettes, as presented in Figure 4 above, indicates that all briquettes produced with variations in temperature and concentrations of starch and molasses binders exhibited consistently low ash levels. All samples complied with the quality standard stipulated in SNI 01-6235-2000, which mandates an ash content of ≤ 8%. Sample 12 (350°C, 60 mesh, 20% starch) exhibited the lowest ash content at 2.2%, whereas sample 17 (350°C, 100 mesh, 15% starch) demonstrated the highest ash content at 6.64%. An independent t-test conducted at the 95% confidence level revealed a significant difference in ash content between samples with different binder types ($p = 0.000$). These results suggest that binder type influences briquette ash content.

The data further reveal that briquettes utilizing molasses as a binder possessed a higher ash content compared to those using starch. This can be attributed to the presence of inorganic salts (e.g., SO_4^{2-}, Ca^{2+}, Na^{+}) in molasses [17] which may not combust fully and remain as mineral residue. Furthermore, the observed increase in ash content with higher carbonization temperatures aligns with findings from [21] which state that elevated temperatures accelerate material decomposition, thereby increasing the amount of inorganic mineral residue left as ash.. An increase in binder concentration also resulted in higher ash content, a trend that is consistent with previous studies [22] [23] While a high ash content can negatively impact the calorific value of a briquette, it is important to note that ash content alone cannot definitively determine whether the calorific value will be higher or lower, as it is dependently integrated with other proximate analysis parameters such as moisture, volatile matter, and fixed carbon contents [24].

3.3. Compressive Strength

Compressive strength is a critical parameter influencing briquette quality. The pressure applied during the briquetting process enhances the density and compactness of the briquette by reducing its volume and minimizing pore spaces. The compressive strength of a briquette is largely determined by its density, which is, in turn, influenced by the particle size and homogeneity of the constituent materials [25]. It is important to note, however, that compaction pressure does not always directly correlate with reduced friability[26]. A higher compressive strength value generally indicates a superior quality briquette, as it ensures better structural integrity during storage and distribution. The compressive strength values of the palm kernel shell briquettes with variations in binder type and concentration are presented as follows:

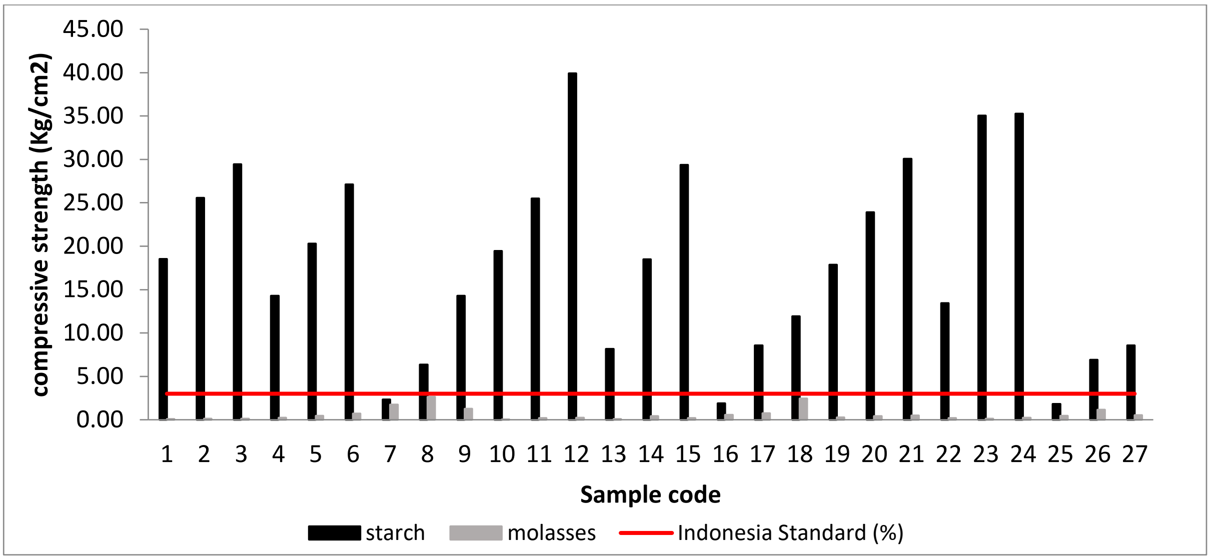

Figure 5. Levels of compressive strength Bio-briquette

Based on Figure 5, all briquettes produced with starch binder, across various temperatures and concentrations, exhibited relatively high compressive strength values and complied with the quality standard specified in SNI 19-4791-1998 (≥ 3 kg/cm²). Sample 12 (350°C, 60 mesh, 20% starch) exhibited the highest compressive strength at 39.91 Kg/cm2. An independent t-test at the 95% confidence level indicated a significant difference in compressive strength between samples with different binder types ($p = 0.000$). These findings indicate that binder type significantly affects the briquette's compressive strength.

In contrast, briquettes utilizing molasses as a binder demonstrated significantly lower compressive strength and failed to meet the stipulated SNI. The higher moisture content inherent in molasses, compared to starch paste, is suspected to be a primary factor negatively affecting the compressive strength. Furthermore, the manual mixing process of charcoal and binder likely contributed to the variability in the strength values obtained. This method introduces the potential for inhomogeneity in the mixture, ultimately compromising the final briquette quality. The manual pressing operation also resulted in non-uniform applied pressure, which directly influences the resulting density and mechanical resistance of the briquettes.

The results also indicate trends related to process parameters. The increase in compressive strength observed with higher carbonization temperatures aligns with findings from other studies [27]. Elevated carbonization temperatures promote the breakdown of organic material into finer particles, resulting in a denser and mechanically stronger briquette structure. Similarly, an increase in binder concentration corresponded with higher compressive strength, which can be attributed to the binder's role in enhancing particle cohesion and overall briquette density[28].

3.4. Calorific Value

Calorific value refers to the amount of heat released per unit mass during the complete combustion of a combustible material. It is the primary parameter for determining the quality of a briquette fuel and is the most critical indicator of the quality of charcoal briquettes as an energy source. The calorific value of a material reflects its energy content and serves as a key indicator of its suitability for use as a fuel [19]. A higher calorific value indicates a greater fixed carbon content within the briquette, signifying superior quality. This is because the combustion process relies on carbon reacting with oxygen to release heat. Consequently, the calorific value of charcoal briquettes is directly influenced by their fixed carbon content [24]. The calorific values of the palm kernel shell briquettes, with variations in temperature, charcoal particle size, and binder type and concentration, are presented as follows:

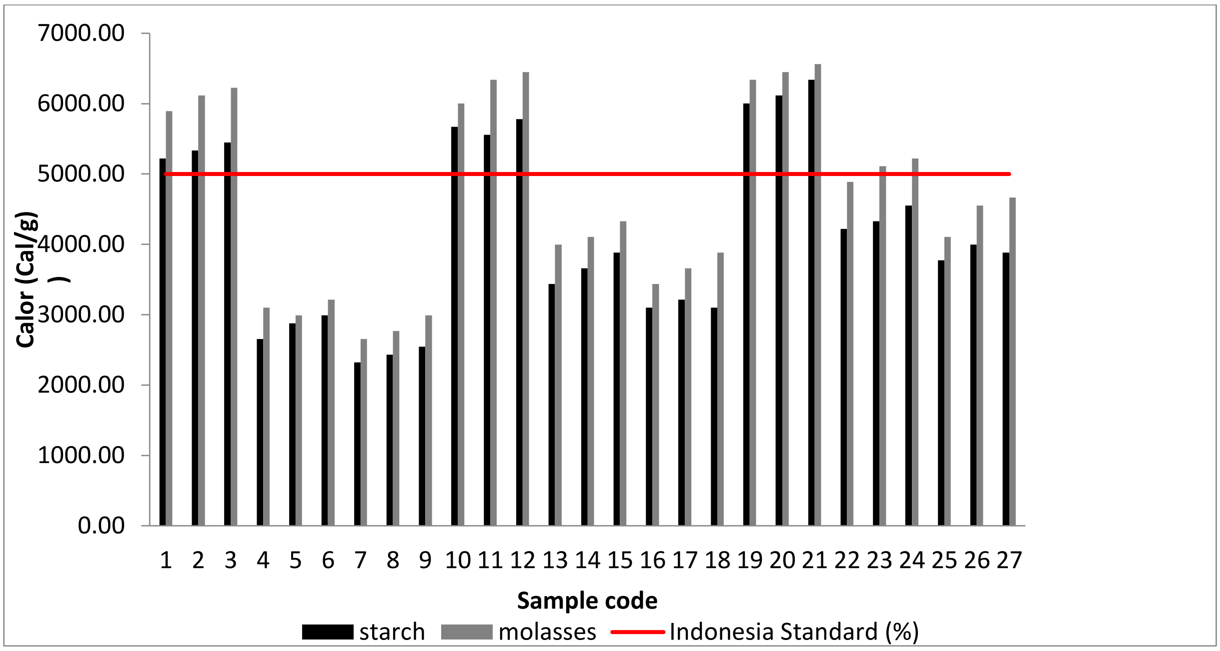

Figure 6. Calor Value of Bio-briquette

Based on Figure 6, several briquettes produced with variations in temperature and concentrations of starch and molasses binders exhibited high calorific values, complying with the quality standard of SNI 01-6235-2000, which stipulates a minimum value of ≥ 5000 Cal/g. The briquettes that met this standard were samples with codes 1, 2, 3, 10, 11, 12, 19, 20, and 21. The highest calorific value of sample 21 (400°C, 60 mesh, 20% molasses) is 6561.49 Cal/g. An independent t-test at the 95% confidence level indicated no significant difference in calor value between samples with different binder types ($p = 0.080$). These findings indicate that binder type does not affect the briquette's calorific value.

A key commonality among these compliant briquettes is the particle size of the palm kernel shell charcoal, which was 60 mesh. The results indicate that the particle size of the charcoal had a more pronounced influence on the calorific value compared to the effects of carbonization temperature and the type or concentration of the binder. A smaller particle size increases the combustion rate, thereby enhancing the efficiency of heat release. The specific influence of particle size can, however, be dependent on the type of biomass used [29]. Furthermore, the concentration of the binder also affected the calorific value. A higher binder concentration generally led to a higher calorific value [30][24]. as the carbon content in the binder itself contributes to the overall energy potential of the briquette[25]. Briquettes incorporating molasses as a binder demonstrated a higher calorific value than those using starch. This is attributed to the high sugar content in molasses, which releases more energy upon combustion. The calorific value of the briquettes produced has approximated the calorific value of coal, namely 6158 cal/g [26] So that palm shell briquettes have the potential to be used as co-firing in combustion in PLTUs when regarded from the calorific value produced.

3.5. Carbon monoxide (CO) emissions

Carbon monoxide (CO) is a product of the incomplete combustion of carbon-containing compounds in fuel. In addition to being emitted by motor vehicles, the combustion of briquettes also contributes to CO pollution. Higher CO emissions from briquette combustion indicate lower briquette quality. Consequently, the CO concentration is a key determinant of briquette quality; a lower CO value signifies a superior briquette. While calorific value is a crucial parameter for determining briquette quality, it is not the sole factor. Therefore, from the 27 sample variations in this study, only 12 variations with a calorific value above 5000 cal/g were selected for further CO emission testing. The results of the CO gas concentration tests for each of these variations are presented below.

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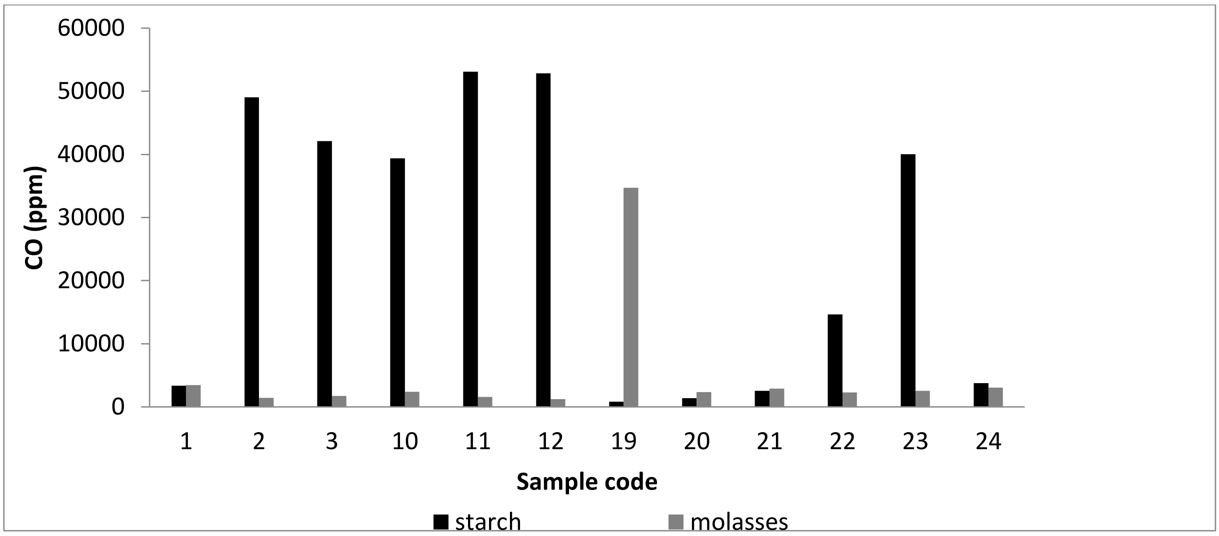

Figure 7. CO concentration of Bio-briquette

The research data presented in Figure 7 indicate that the CO gas concentrations from the briquettes were notably high. The data show that briquettes using a molasses binder generally produced lower CO emissions compared to those using a starch binder. The lowest recorded CO emission was 812 ppm for starch-bound briquettes (15% concentration, sample 19) and 1242 ppm for molasses-bound briquettes (25% concentration, sample 12). To contextualize these results, a comparison with prior studies reveals a mixed picture. The emissions from this study are relatively high compared to the 712 ppm reported for coffee husk and coconut shell briquettes with a starch binder [27] Conversely, the emissions are significantly lower than the 4713 ppm reported for sugarcane bagasse and coconut shell briquettes with a tapioca binder [28].

The primary factor contributing to the high CO emissions across all samples is likely an insufficient supply of oxygen within the combustion stove, leading to incomplete combustion. Under these oxygen-starved conditions, carbon is preferentially converted to CO instead of being fully oxidized to CO_2. This aligns with the findings of [29] which state that inadequate air supply in a biomass stove combustion chamber results in incomplete combustion and elevated CO emissions..

Furthermore, briquette density significantly impacts CO production. Briquettes with higher density have a more compact structure, resulting in a slower combustion rate. This slower burn, if not accompanied by sufficient oxygen, promotes the formation of CO as the fuel does not combust completely. This is evidenced by the data: starch-bound briquettes, which exhibited higher compressive strength (indicating higher density), also produced higher CO emissions than the less dense molasses-bound briquettes. In highly dense briquettes, oxygen cannot diffuse effectively into the inner core, causing uneven combustion and high, unstable CO emissions. Based on the CO emission results, the bio-briquettes from this study possess relatively high CO levels, making them unsuitable for use in open, uncontrolled environments or for household applications without Air Pollution Control Devices (APCDs). However, their application is better suited to industrial boiler systems, where combustion conditions and emissions can be carefully managed and monitored; however, further testing is still needed under full-scale boiler conditions.

This aligns with the Indonesian government's national energy policy, which promotes sustainable development through long-term energy planning. One key initiative in this effort to reduce boiler emissions is the implementation of biomass co-firing systems, for which these briquettes could be a potential feedstock.

Several limitations should be acknowledged in this study. Manual drying and molding may influence the consistency and final quality of the bio briquettes. Additionally, the combustion conditions applied were not optimal, indicating a need for further research to optimize combustion parameters, especially for full-scale boiler applications.

4. Conclusions

This study shows that the palm kernel shell charcoal briquettes produced meet the Indonesian National Standard (SNI) for moisture content, ash content, compressive strength, and calorific value. The type of binder (molasses vs. starch) significantly affected moisture content, ash content, and compressive strength, as determined by an independent t-test at the 95% confidence level ($p < 0.05$). Briquettes with molasses binder produced the lowest moisture content (1.1%) in sample 17 (temperature 350°C, particle size 100 mesh, molasses concentration 20%). Conversely, the starch binder produced the lowest ash content (2.2%) and the highest compressive strength (39.91 kg/cm²) in sample 12 (temperature 350°C, particle size 60 mesh, starch concentration 20%). Furthermore, the calorific value was primarily influenced by charcoal particle size, with smaller particles yielding higher values. The highest calorific value (6561.49 cal/g) was obtained from sample number 21 (temperature 400°C, particle size 60 mesh, molasses concentration 20%). Although all briquettes met SNI for key quality parameters, all samples produced high carbon monoxide (CO) emissions. Therefore, these briquettes are not yet recommended for household use. However, the briquettes are considered potentially suitable for application in industrial boilers equipped with air pollution control devices (APCDs), where CO emissions can be effectively managed. Further research is needed to optimize the combustion process to reduce CO emissions and to test the briquettes' performance at full-scale boiler conditions.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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