

Characteristics of Hybrid Biopellet based on Oil Palm Wood and Natural Activated Charcoal as a Renewable Alternative Energy Source

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ABSTRACT

Oil palm wood is biomass waste with a high abundance of energy which has the potential to be used as a raw material in the production of biopellet as an alternative energy source. However, oil palm wood possesses low density and calorific value. This study aims to evaluate the characteristics of biopellet formed through the hybridization of oil palm wood and natural activated charcoal. The natural activated charcoal filler was made from coconut shell and tapioca starch was used as a binder at a ratio of 150 g. Hybrid biopellet were produced using a roller wood machine with varying amounts of natural activated charcoal content: 200 g, 300 g, and 400 g per kg of raw material. The quality of the hybrid biopellet was evaluated based on the SNI 8021-2014 standards, including density, moisture content, ash content, volatile matters, fixed carbon, and calorific value. The results show that the hybridization of natural activated charcoal significantly influences the quality of the biopellets. Overall, the characteristics of the hybrid biopellet have met the SNI 8021-2014 standards, except for the ash content. The HBC-400 hybrid biopellet type exhibited the highest quality, with a density of 0.886 g/cm³, moisture content of 7.33%, ash content of 2.22%, fixed carbon of 62.12%, and calorific value of 4822 Cal/g. Oil palm wood and natural activated charcoal-based hybrid biopellet have the potential to be used as a renewable alternative energy source.

Keywords: oil palm wood, hybrid biopellet, natural activated charcoal, alternative energy source.

INTRODUCTION

The availability and sustainability of energy have become major issues for the survival of humanity, faced by almost all countries in the world. Energy consumption increases annually, reaching 1.6–1.8% (Li 2017), while the depletion of fossil energy reserves exacerbates the global energy problems that need to be addressed seriously. Many countries have committed to transitioning from fossil energy to cleaner energy through the Paris Agreement. However, global fossil energy consumption remains remarkably high to this day. Beyond Petroleum in the Statistical Review of World Energy 2021 stated that global fossil energy consumption reached 462.77 exajoules in 2020 (Pahlevi 2022). China accounted for 122.67 exajoules of fossil energy consumption,

representing 26.5% of the world's total. The United States ranked second with a consumption of 71.69 exajoules. Furthermore, the European Union, India, and Russia ranked third, fourth, and fifth, with 39.62, 28.71, and 24.47 exajoules, respectively. Indonesia ranked twelfth, with fossil energy consumption reaching 7.1 exajoules (Pahlevi 2022). Several previous studies have examined the relationship between energy consumption, economic growth, and carbon dioxide (CO₂) emissions, which has become an important issue in the past few decades (Odugbesan and Rjoub 2020; Waheed et al. 2019). Other studies have evaluated the effectiveness of renewable energy development for transitioning from fossil fuels by 2050 (Holechek et al. 2022). Abas et al. (2015) have reviewed the use of fossil fuels and future energy technologies. The use of fossil fuels

has led to an increase in CO₂ emissions. To slow down climate change and develop sustainable energy resources, the global community must support the significant energy transition from fossil fuels to renewable energy sources.

One of renewable energy forms is biomass. Biomass can be obtained from various sources, including wood waste and agricultural residues. However, both materials tend to have high moisture content and poor combustible properties (Kansai et al. 2018; Lee and Kim 2020). Hybrid biopellet technology is one solution to improve the quality of biomass for combustion. Several previous studies have reported the use of biomass as a raw material for biopellet production. Cahyani et al. (2023) evaluated the characteristics of biopellet made from coffee grounds and pine wood charcoal. The moisture content, ash content, and calorific value of the coffee grounds biopellets met the Indonesian National Standard (SNI 8021-2014), but the density and ash content were still below the standard values. Rice husk and coconut shell biopellets with a 50:50 composition and the addition of 6% binder resulted in a heating value of 4966 Cal/g (Yuliah et al. 2017).

The utilization of wood waste as raw material for biopellets, such as Madan wood (Kongprasert et al. 2019), Kaliandra wood (Permatasari et al. 2022), and hardwoods from Korea (camellia oil cake, toothache tree, and mulberry tree) (Ciupek and Gołóś 2020; Lee et al. 2020), has also been reported by several previous researchers. Pellets made from hardwood chips and camellia flower oil cake showed the highest calorific value of approximately 17–18 MJ/kg. In addition, some researchers have also developed Empty Fruit Bunches (EFB) as raw material for biopellet (Nasrin et al. 2022; Rusdianasari et al. 2023; Wistara et al. 2017). Hybrid biopellet made from 90% EFB charcoal and 10% durian peel with maize starch binder had a calorific value of 10.3 MJ/kg. These hybrid biopellet have the potential as a source of renewable energy (Selvarajoo et al. 2021).

Indonesia has a high abundance of oil palm trunk as biomass waste (Figure 1). Indonesia is one of the world's largest producers of palm oil. According to the statistical data from 2017–2019 by the Directorate General of Plantations, Ministry of Agriculture, the total area of oil palm plantations in Indonesia has been increasing over the years. In 2019, Indonesia had a total oil palm plantation area of 14.67 million hectares

(Pertanian 2018). Oil palm trunk biomass is generated from the regeneration of old (25–30 years) and unproductive plants. If the average replanting rate is 4% per year of the total plantation area and can produce an estimated volume of oil palm wood (OPW) of around 200 m³/ha (Hambali and Rivai 2017), then in 2020, it is estimated that there are 586,800 hectares of replanting area, producing approximately 117.36 million m³ of oil palm wood (OPW). Recently, oil palm trunk has started to be used for particleboard, plywood, lumber, and blockboard (Mawardi et al. 2021a, 2021b, 2023).

Oil palm trunk waste has the potential to be utilized as raw material for biopellet fuel. The trunk consists of the outer part (bark) and the inner part (wood). Wistara et al. (2017) studied the influence of densification temperature on the calorific value of biopellets made from oil palm trunk bark. The resulting calorific value of the pellets ranged from 17.89 to 19.14 MJ/kg. However, there is no reported study on biopellets made from the inner part of the oil palm trunk, known as oil palm wood (OPW), which has low density and low calorific value characteristics.

In this research, hybridization of OPW with natural activated charcoal (NAC) from coconut shell was conducted to enhance the characteristics of biopellet. Tapioca starch was used as a binder. The evaluation of hybrid biopellet characterization was carried out following the Indonesian wood pellet standard



Figure 1. Oil palm trunk

SNI 8021-2014 (Badan Standarisasi Nasional 2014). This research is important as it aims to reduce biomass waste and produce effective and environmentally friendly solid biofuel.

MATERIALS AND METHODS

Materials

The materials used in forming the hybrid biopellet consist of oil palm wood (OPW) particles as the main material (Figure 2a), NAC from coconut shell as the filler (Figure 2b), and tapioca starch as the binder (Figure 2c). Tapioca starch contains amylose and amylopectin, and the two components have different roles in the binding process. Amylopectin is a substance that acts as an adhesive, while amylose acts as a hardener. Oil palm trunks aged 25–30 years, which had been felled and become waste, were collected from oil palm plantations in Aceh, Indonesia. The oil palm trunks were stripped of their bark and then cut into small pieces using a chainsaw. Subsequently, they were shaped into chips to facilitate the grinding process using a disk mill. The OPW particles were then sorted to obtain particles that passed through a 60-mesh sieve. The OPW particles were dried under sunlight until they reached a moisture content of 15–20%. The NAC used as a filler was derived from coconut shell waste (*Cocos nucifera*). The coconut shells were carbonized by placing them in a drum and burning them for 30 minutes. The carbonization process system was carried out stationary at the optimum temperature of 450 °C. This process is carried out with the participation of air. The resulting coconut shell charcoal was ground using a grinder machine until it reached a size of 150 mesh. The

Table 1. Chemical content of the OPW (Dungani et al. 2018)

Chemical	Content (%)
Holocellulose	42–45
Hemicellulose	12–17
Cellulose	29–37
Lignin	18–23
Extractives	4–7
Ash	2–3

Table 2. Proximate and ultimate analysis of NAC (Iqbalidin et al. 2013)

Proximate and ultimate analysis	Content (%)
Proximate	
Volatile matter	28.46
Fixed carbon	69.49
Ash content	2.05
Ultimate	
Carbon	80.13
Hydrogen	2.36
Nitrogen	1.10
Sulphur	0.06
Oxygen	16.35

natural binder used was tapioca starch, which was obtained from the local market. Tapioca starch contains approximately 15% amylose and 85% amylopectin, fineness 90-100 mesh, moisture content 13–15%, and ash 0.4–0.5% (Asrofi et al. 2021; Subagyo and Amin 2015). Ariefin (Ginting et al. 2019) reported that tapioca starch has a high adhesive viscosity and is a suitable ingredient for the production of biobriquettes or biopellets. Table 1 and Table 2 present the chemical composition of the OPW and the proximate and ultimate analysis of the NAC.

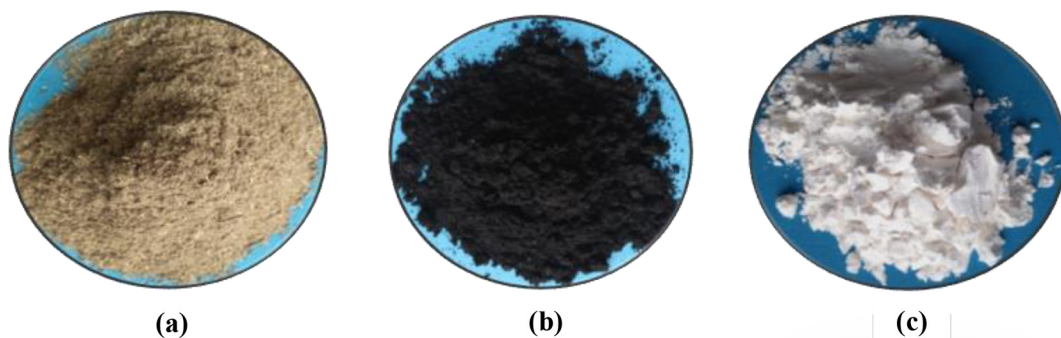


Figure 2. Biopellet hybrid forming material

Hybrid biopellet production process

The formation of hybrid biopellet was carried out using a Roller TM300 wood pellet machine (Indonesia) with a capacity of 300 kg/hour (Figure 3). The die has 369 holes with a passage diameter of 8 mm and a height of 36 mm. Prior to pelletizing, the OPW particles, NAC, and tapioca starch were mixed and stirred until thoroughly blended using a manual mixer with 100 rpm for 5 minutes. Then, hot water (100 °C) at a ratio of 500 ml per kg of raw material was poured and stirred until homogeneous. The mixture of OPW-based hybrid biopellets was fed into the wood pellet machine. The composition of the resulting hybrid biopellets is shown in Table 3. After the pelletizing process, the hybrid biopellets were dried under sunlight until completely dry (about three days) before undergoing testing.

Characteristics of hybrid biopellet

The characterization of hybrid biopellets is conducted according to the SNI 8021-2014 standard, including the evaluation of density, moisture content, ash content, volatile matters, fixed carbon, and calorific value.

Density testing

Three samples for each biopellet variation were tested for density. The dimensions and weight of the samples were measured and weighed, and then the density of the biopellet was calculated using equation (1).

$$\rho (\text{density}) = \frac{\text{mass (g)}}{\text{Volume (cm}^3\text{)}} \quad (1)$$

Moisture content testing

The moisture content characteristic of the biopellets was determined by placing 1 g of the sample in an oven at a temperature of 1035 ± 2 °C for 24 hours until a constant weight was achieved (Cahyani et al., 2023). The sample was then cooled for 15 minutes and weighed. Equation 2 was used to calculate the moisture content of the biopellets.

$$MO (\%) = \frac{\text{in the oven (g)} - \text{weight after drying in the oven (g)}}{\text{weight after drying in the oven (g)}} \times 100\% \quad (2)$$

Ash content testing

The ash content was analyzed by placing 1 g of the sample in a crucible and heating it in a

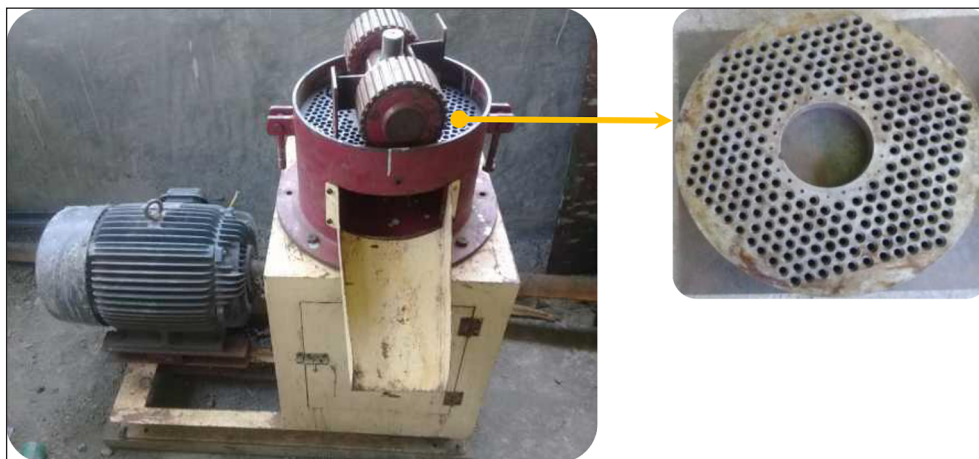


Figure 3. Wood pellet machine and die

Table 3. Formulation of hybrid biopellet per kg

Sample denotation	OPW	NAC	Tapioca starch
HBC-0	850 g	0 g	150 g
HBC-200	650 g	200 g	
HBC-300	550 g	300 g	
HBC-400	450 g	400 g	

furnace for 6 hours at temperatures ranging from 600 °C to 900 °C (Cahyani et al. 2023). The sample was then cooled in a desiccator and weighed. The ash content was calculated using formula (3).

$$\text{Ash content (\%)} = \frac{\text{weight of ash (g)} - \text{weight of cup (g)}}{\text{weight of sample (g)}} \times 100\% \quad (3)$$

Volatile matters testing

The volatile matter characteristic was measured by placing approximately 1 g of the sample in a porcelain container and heating it in a furnace at a temperature of 900 °C for 7 minutes. The resulting combustion residue was cooled in a desiccator for approximately 1 hour until it reached room temperature. The volatile matter was then calculated using equation (4).

$$\begin{aligned} \text{Volatile matters (\%)} &= \frac{\text{Loss in weigh due to removal of volatile matter (g)}}{\text{weight of fuel sample for testing (g)}} \times 100\% \quad (4) \end{aligned}$$

Fixed carbon testing

The fixed carbon was determined by subtracting the percentage of moisture content, volatile matter, and ash content from the sample. Equation 5 was used to calculate the fixed carbon.

$$\text{Fixed carbon (\%)} = 100 (\%) - \text{moisture content (\%)} - \text{volatile matter (\%)} - \text{ash content (\%)} \quad (5)$$

Calorific value testing

Calorific value is an important characteristic of a fuel. The evaluation of the calorific value of the

biopellets was performed using an Automatic Bomb Calorimeter - K88890 made in the USA (Figure 4).

RESULTS AND DISCUSSION

Figure 5 shows the hybrid biopellet based on OPW with NAC from coconut shell as a filler and tapioca starch as a binder. From the color, the HBC-0 biopellet (pure OPW) had a brighter color compared to the biopellet with the addition of 200 g, 300 g, and 400 g of NAC. The hybrid biopellet with the addition of 400 g of NAC (HBC-400) had the darkest appearance compared to other hybrid biopellets. The addition of activated charcoal increased the intensity of the black color in the hybrid biopellets. The intensity of color in the produced biopellets in the following order: HBC-0, HBC-200, HBC-300, and HBC-400. The black color of the activated charcoal had influenced the color contour of the resulting hybrid biopellets. The difference in color contour of the biopellet indicates differences in the composition of the biopellets.

Characteristics of hybrid biopellet

In order to determine the quality of OPW hybrid biopellet with the addition of NAC from coconut shell, characteristic tests were conducted. The results of the characteristic testing of OPW biopellet are as follows.

Density of hybrid biopellet

Density is one of important factors in the characteristics of biopellets. The density value



Figure 4. Automatic bomb calorimeter-K88890

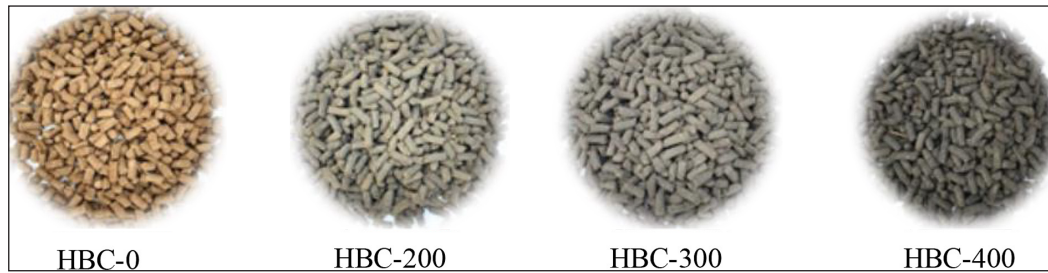


Figure 5. Hybrid biopellet based on OPW

will affect other characteristics such as moisture content and calorific value. Additionally, high density can facilitate handling, storage, transportation of pellets, and pellet durability. Density value is influenced by several variables such as raw material density, particle size, die hole design, and compression force (A. Ginting et al. 2019; Macák et al. 2015). Figure 6 shows the density of biopellet with various amounts of NAC. The density of biopellet ranged from 0.657 to 0.886 g/cm³, with the hybrid biopellet type HBC-400 having the highest density and the lowest value in the biopellet without fillers (HBC-0). In this study, the gradual addition of NAC increased the density value. The low density of HBC-0 and HBC-200 types can be attributed to the larger volume of OPW. In addition to the effect of a higher amount of OPW, the density of biopellet is also influenced by the density of the raw materials, with OPW having a density of 0.28 g/cm³. Meanwhile, the density of activated charcoal is higher, ranging from 0.40 to 0.54 g/cm³. The test results indicate that HBC-300 and HBC-400 biopellet types have met the requirements of SNI 8021:2014.

Moisture content of hybrid biopellet

Figure 7 shows the moisture content values of OPW-based biopellet with NAC. The moisture content values are inversely proportional to density. The moisture content of OPW biopellet produced ranged from 7.33% to 12.83%. Biopellet with 100% OPW particle composition (HBC-0) had the highest moisture content value of 12.83%. On the other hand, the lowest moisture content (7.33%) was observed in the biopellet treatment with a composition of 450 g OPW particles, 400 g NAC, and 150 g tapioca starch adhesive (HBC-400). The high water absorption capacity of pure OPW biopellets is attributed to the hygroscopic characteristics of OPW, which has poor water resistance. The moisture content tends to decrease with a decrease in the proportion of OPW and an increase in NAC. The lower moisture content of NAC compared to OPW particles results in lower moisture content in the produced biopellets. This is consistent with previous research (Badri, Arief, and Kurniawan 2022) demonstrating that the higher the addition of rice husk charcoal in the biopellet composition, the lower the moisture content produced. High moisture content will affect the calorific value.

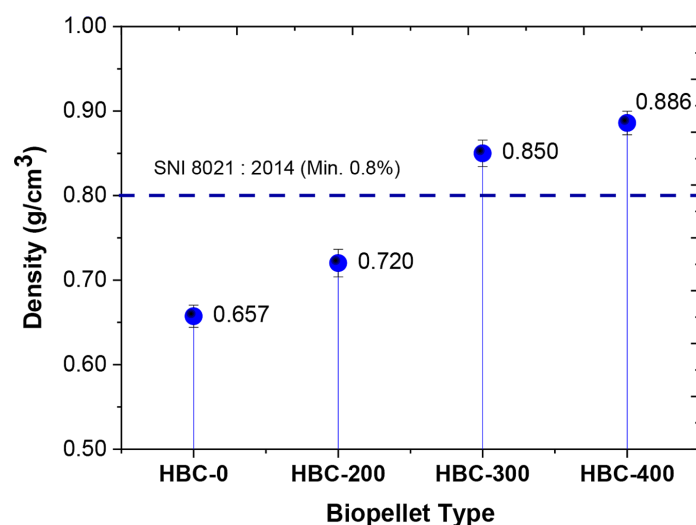


Figure 6. Density of hybrid biopellet

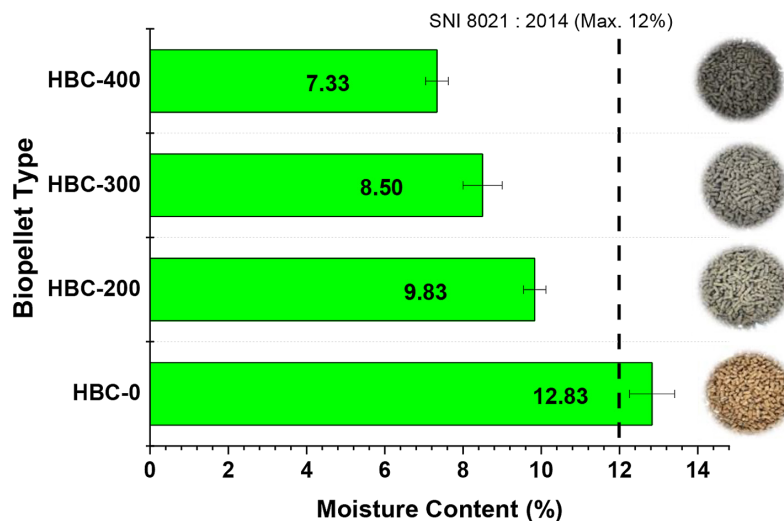


Figure 7. Moisture content of hybrid biopellet

High moisture content causes low combustion calorific value and fire temperature during combustion. This phenomenon is due to endothermic evaporation due to the total energy required to bring it to the combustion temperature. During combustion, the moisture content in the biopellets will absorb heat or heat for the evaporation process, which will significantly reduce the calorific value of the biopellets.. The moisture content of all types of hybrid biopellet produced has met the SNI 8021-2014 standard, which specifies a moisture content of less than 12%, except for HBC-0 biopellet.

Ash content of hybrid biopellet

The ash content characteristic is one of important characteristics of biopellets. High ash content will cause a decrease in the heat generated due

to the accumulation of ash during combustion. Ash, especially in solid fuel, is a ballast and non-combustible part of the fuel that does not raise the calorific value of fuel, artificially lowering it by its value. Excessive amounts of ash can also affect the excessive amount of dust in the exhaust gas, and this will result in a deterioration of the air quality at the combustion site of fuel with a high ash content, hence currently, the search for fuels with low ash content as ecologically valuable fuel but also with little impact on the quality of the environment. This condition has a negative impact on biopellet and can also result in crust accumulation in the combustion chamber. Figure 8 shows the ash content values of OPW-based biopellet with NAC. The biopellet produced had ash content ranging from 1.64% to 2.22%, with the highest ash content recorded in pure OPW

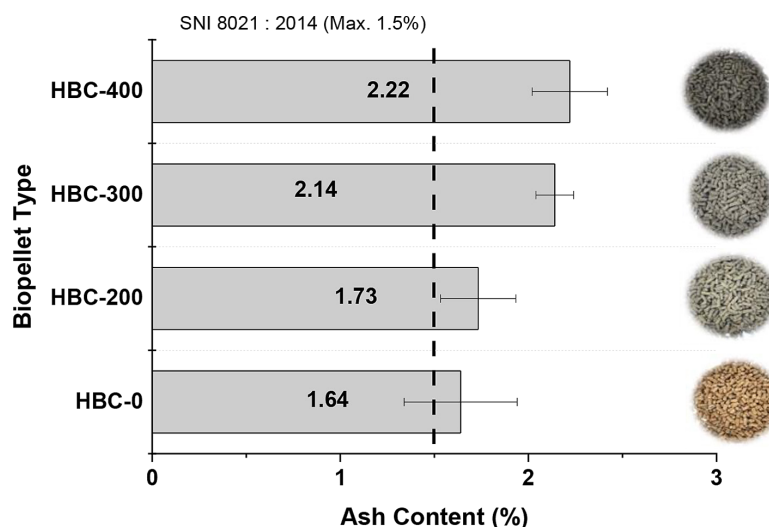


Figure 8. Ash content of hybrid biopellet

biopellet(HBC-0), and the lowest ash content in hybrid biopellet with the addition of 400 g NAC (HBC-400). Ash content is closely related to the calorific value. A higher percentage of ash indicates a larger amount of unburned products, resulting in a lower calorific value (Colantoni et al. 2021). The ash content is influenced by the type of raw material, as the mineral content varies for each type of raw material. The ash content of OPW is higher compared to NAC. OPW particles have an ash content composition of 2–3% (Dungani et al. 2018), while coconut shell charcoal has an ash content of 2.05% (Iqbalidin et al. 2013). The ash content is also influenced by the silica content in the raw material. Furthermore, the increase in ash content may be caused by incomplete carbonization processes. The presence of air during carbonization can cause the formed charcoal to turn into ash (Wistara et al. 2017). The ash content values of all produced biopellet do not meet the SNI 8021-2014 standard, which requires a maximum of 1.5% ash content.

Volatile matters of hybrid biopellet

The volatile matter content in fuel determines the burning time, burning rate, and the amount of smoke produced during the combustion process (Ciupek et al. 2019; El-Sayed and Khairy 2018). The results show that the highest volatile matter content (69.83%) was found in biopellet with pure OPW composition and tapioca starch adhesive. Meanwhile, the lowest volatile matter content of 47.33% was obtained from HBC-400 hybrid biopellet. The increase in volatile matter content tends

to be inversely proportional to the increase in the percentage of NAC. The higher the percentage of NAC used, the lower the volatile matter content of the biopellets, and vice versa. This is because some of the components of NAC have evaporated during the carbonization process, resulting in a lower volatile matter content in the biopellets. The carbonizate produced in the process of carbonization does not have in its structure the gaseous parts (H_2 or O_2) that have been degassed in the process of fuel smoldering, hence the higher proportion of activated carbon in the final fuel affects the lower content of volatile parts. Volatile matters are also influenced by the organic compounds in the materials, including carbon, oxygen, and hydrogen (Ajimotokan et al. 2019; Kawale and Kishore 2020). The results show that the volatile matter content of OPW-based biopellet with NAC is relatively high, but these results are still below the maximum value required by the SNI 8021-2014 standard, which is 80%.

Fixed carbon of hybrid biopellet

Fixed carbon is defined as the carbon fraction in biomass, excluding the fractions of water, volatile matters, and ash. The fixed carbon content serves as a parameter for fuel quality as it affects the calorific value. The fixed carbon content of the biopellet produced in this study ranged from 23.25% to 62.12%, with the highest fixed carbon content found in the hybrid biopellet with the addition of 450 g of NAC (HBC-400). The lowest fixed carbon content was observed in the biopellet treatment with 100% OPW particles and tapioca

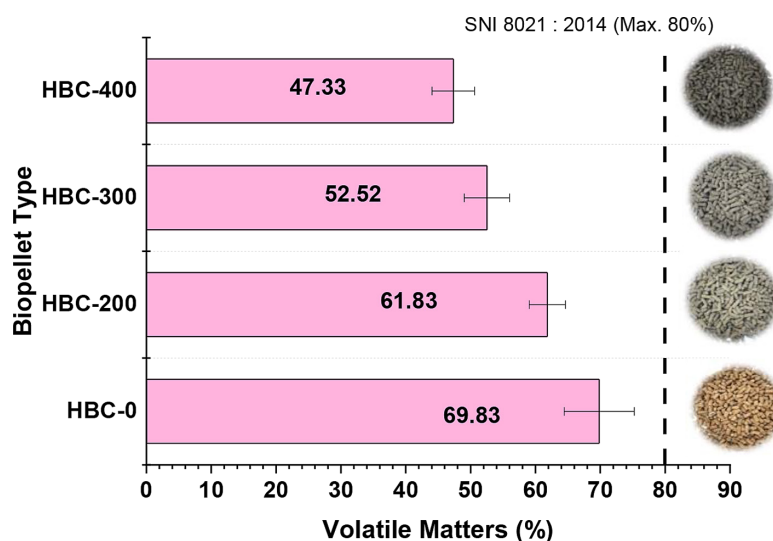


Figure 9. Volatile matters of hybrid biopellet

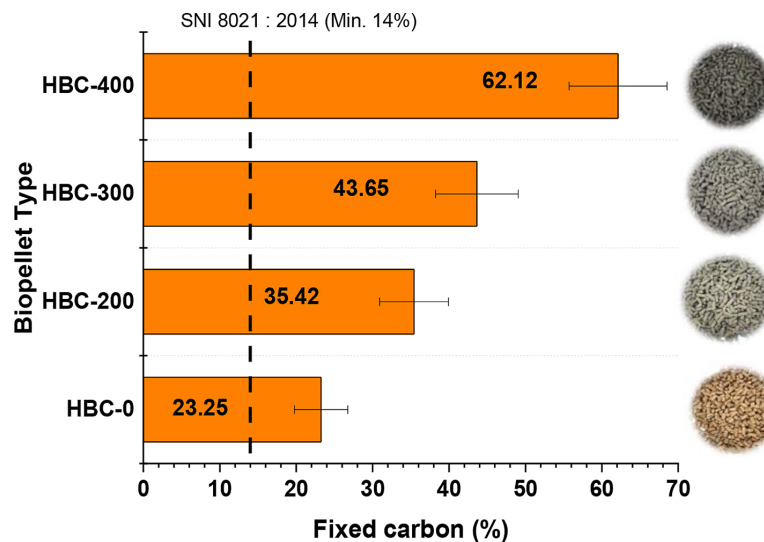


Figure 10. Fixed carbon of hybrid biopellet

starch adhesive. Figure 9 shows an increase in fixed carbon content with the increase in NAC. This increase is attributed to the high fixed carbon content of the raw material, coconut shell charcoal (69.49%) (Iqbalidin et al. 2013). Fixed carbon is influenced by its constituent elements such as carbon, hydrogen, and oxygen (Jeguirim, Limouisy, and Dutournie 2014). The findings show that the percentage of fixed carbon is influenced by the level of volatile matters, and a higher percentage of fixed carbon will subsequently increase the calorific value. A high level of fixed carbon indicates that the fuel tends to burn slower than fuels with lower fixed carbon levels (Martinez et al. 2019). All biopellet produced in this study have met the SNI 8021-2014 standard, which requires a minimum fixed carbon content of 14%.

Calorific value of hybrid biopellet

Calorific value is a key parameter for the quality of biopellet and is crucial in determining the efficiency of a fuel. The calorific value influences the energy output provided by the biopellets. It is affected by the moisture, ash, volatile matters, and fixed carbon content. The test results show that the calorific value of OPW-based biopellet with the addition of NAC ranged from 2847.22 to 4822.96 Cal/g. The hybrid biopellet with the addition of 450 g of NAC have the highest calorific value of 4822.96 Cal/g, while the lowest calorific value was observed with the addition of 100 g of NAC.

The addition of NAC increased the calorific value of pure OPW biopellet by up to 100%. The

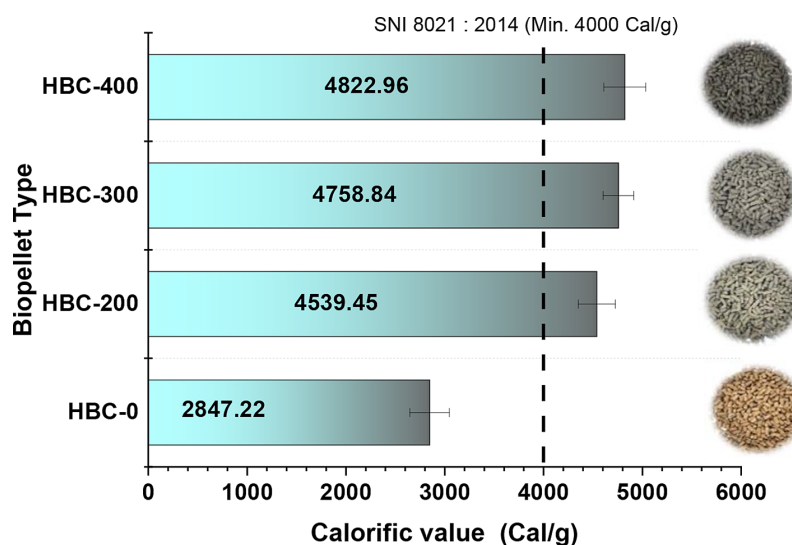


Figure 11. Calorific value of hybrid biopellet

Table 4. Comparison of proximate and calorific value of various biopellets

Study	Parameters of proximate and calorific						Ref.
	Density (g/cm ³)	Moisture content (%)	Ash content (%)	Volatile matters (%)	Fixed carbon (%)	Calorific value (Cal/g)	
SNI 8021: 2014	Min. 0.8	Max. 12	Max. 1.5	Max. 80	Min. 14	Min. 4000	
Hybrid biopellet based on OPW and NAC	0.657–0.886	7.33–12.83	1.64–2.22	47.33–68.83	26.25–62.12	2847.22–4822.96	This study
Biopellet from empty fruit bunch and durian rinds with cornstarch adhesive	-	4.23–6.70	1.87–6.14	79.49–92.44	2.88–16.14	3572.91–5776.65	(Selvarajoo et al. 2021)
Biopellet from camellia oil cake	-	7.24	2.12	76.52	21.36	4445.45–4880.20	(C.-Y. Lee et al. 2020)
Biopellet from nifah fruit skin	1.41	1.28	0.51	21.30	76.88	7313.40	(Abdurrahman et al. 2020)
Biopellet made of Calliandra Wood	-	3.64	0.95	69.43	26.10	13993.00	(Permatasari, Atikayanti, and Ginting 2022)
Briquettes from rice husk	-	7.63–8.52	19.92–20.75	21.70–24.46	47.10–49.63	4860.00–4955.00	(Yuliah et al. 2017)
Low-ash empty fruit bunches (EFB) pellets	-	6.95–9.63	1.58–4.66	71.31–72.87	15.93–17.07	3139.29–5161.86	(Nasrin et al. 2022)
Biopellets from spent coffee grounds and pinewood charcoal	0.59–0.74	3.31–5.37	2.56–3.23	43.87–59.28	34.09–49.20	5408.00–5950.00	(Cahyani et al. 2023)

higher the percentage of NAC, the higher the calorific value of the biopellets. The calorific value is directly proportional to the fixed carbon content, indicating the amount of combustible solid material. The calorific value is also related to the moisture content. High moisture content leads to a decrease in calorific value as the biopellet become less combustible (Cahyani et al. 2023). These findings are consistent with previous studies that reported an increase in the calorific value of rice husk biopellet with the addition of rice husk charcoal (Yuliah et al. 2017). The role of raw materials in the composition of biopellet significantly influences the calorific value of the resulting biopellets. The higher the calorific value of the raw material, the higher the calorific value of the biopellet produced. The calorific value of the hybrid biopellet produced in this study have met the SNI 8021-2014 wood pellet standard, which requires a minimum calorific value of 4000 Cal/g, except for the biopellet produced with pure OPW (HBC-0). In general, the hybrid biopellet produced in this study have met the SNI 8021-2014 standard. Table 4 presents a comparison of the proximate characteristics and calorific value of the biopellet produced in this study with those reported by previous researchers.

CONCLUSIONS

This study evaluated the characteristics of OPW-based hybrid biopellet with the addition of NAC as a filler and tapioca starch as a binder. The influence of the NAC percentage in OPW-based hybrid biopellet was investigated in terms of proximate properties and calorific value. Increasing the percentage of NAC had effects on the density, ash content, fixed carbon, and calorific value of OPW-based hybrid biopellets. Overall, all types of hybrid biopellet produced in this study have met the SNI 8021-2014 standard, except for HBC-0. Biopellet with a hybrid composition of OPW particles, NAC, and tapioca starch (HBC-400) exhibited the best quality compared to other biopellets, with a calorific value of 4822 Cal/g, fixed carbon content of 62.12%, ash content of 2.22%, moisture content of 7.33%, and density of 0.886 g/cm³. The HBC-400 hybrid biopellet has the potential to be used as a renewable alternative fuel source.

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