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Characteristics of bio-briquettes from candlenut shells as a renewable energy: Selection of adhesive type, adhesive concentration, and biochar particle size

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ABSTRACT

The production and characterization of bio-briquettes from candlenut shells biochar were conducted, with an in-depth investigation into the selection of adhesive type (starch, molasses, tar), adhesive concentration (10%, 20%, 30%), and biochar particle size (20 mesh, 40 mesh, 80 mesh) using the analytical hierarchy process (AHP). The results highlighted the optimal bio-briquette quality by using starch, with an adhesive concentration of 30% and a biochar particle size of 80 mesh. The produced bio-briquettes met the quality requirements of the Indonesian National Standard (SNI No. 1-3624-2000), as well as other bio-briquette standards. With a remarkably high calorific value, 8254.25 cal/g, these bio-briquettes demonstrate great potential as an affordable renewable energy.

Keywords: bio-briquettes; candlenut shells; pyrolysis; renewable energy; tapioca.

INTRODUCTION

The demand for energy and fossil fuels continues to increase every day, contributing to the rise in greenhouse gas emissions, environmental pollution, and global warming. Furthermore, the inefficient combustion of biomass for cooking and other energy production purposes also exacerbates these hazards. Approximately 3 billion people worldwide face challenges in accessing sustainable cooking energy due to limited technology and dependence on conventional fuels such as kerosene, liquefied petroleum gas (LPG), as well as firewood and other solid fuels. Therefore, sustainable and renewable energy sources are increasingly being utilized to address the shortage of clean energy in the industrial and agricultural sectors. Biomass, particularly agricultural organic waste, is recognized as a sustainable and clean energy source (Ali et al., 2024). This is because biomass offers several advantages, including being environmentally friendly, clean, affordable, and having a relatively high calorific value (4000–5000 kcal/kg) (Iriany et al., 2016).

Bio-briquettes are a form of renewable energy derived from biomass, produced in the form of molded charcoal blocks made from organic waste, with a high calorific value. Bio-briquettes exhibit favorable energy characteristics, such as high density and higher heating value (HHV) (Iriany et al., 2016). Other advantages include affordability, renewability, being sulfur-free, having a higher calorific value compared to other solid fuels, lower ash content than coal, more complete combustion than coal, and wide availability within local communities (Sanchez et al., 2022), making bio-briquettes highly promising as a renewable energy source for communities, including in rural areas.

The production of bio-briquettes begins with the pyrolysis of biomass to produce bio-char. In this step, the pyrolysis temperature needs to be carefully studied, as it significantly affects the quality of the resulting bio-char. Then, the bio-char is processed into bio-briquettes by adding an adhesive to enhance the bonding between bio-char particles during the compaction process. At this stage, the type of adhesive used plays a crucial role in determining the final quality of the bio-briquettes (Hasibuan et al., 2024). In authors' previous investigation, the effect of pyrolysis temperature, ranging from 250 to 350 °C, on the quality of coffee stem-derived bio-briquettes was evaluated. The increasing of pyrolysis temperature produced bio-briquettes with lower moisture content, as the dehydration process occurs more rapidly at higher pyrolysis temperatures (Hasibuan et al., 2024).

On the other hand, the selection of adhesive type also plays a crucial role in the production of high-quality bio-briquettes. Adhesive can be categorized into organic, inorganic, and composite adhesives. Among these, organic adhesives offer excellent bonding properties and high water resistance. In addition, organic adhesives are widely available, low-cost, possess high calorific value, and have a low ignition temperature (Obi et al., 2022). Furthermore, adhesive type and the adhesive concentration significantly influence the physicochemical properties, combustion performance, and production costs of bio-briquettes (Sanchez et al., 2022).

Several studies have been conducted on the bio-briquettes production using various organic adhesives, particularly focusing on starch, molasses, and tar. Tapioca exhibits good starch quality (70–75%), possesses strong binding capability at elevated temperatures, and is capable of forming a clear amylopectin paste (Aliah et al., 2023). Production of bio-briquettes using starch has been carried out utilizing various biomass feedstocks, including coffee stems (Hasibuan et al., 2024), rice husk and pine flower mixture (Suanggana et al., 2024), as well as a mixture of rubber fruit shells and wood branches (Iriany et al., 2023). The second adhesive is molasses, which is a by-product of the sugar industry in the form of a thick liquid left after the crystallization of sugar. Molasses consists of unrecovered sugars during processing (30–60% by weight), proteins (< 10% by weight), and inorganic minerals (< 10% by weight) (Borowski, 2021). Utilization of molasses as an adhesive for bio-briquettes involved using banana stems (Hasibuan et al., 2024), coconut shells (Waluyo et al., 2023), as well as a mixture of filter cake (*blotong*) and banana stems (Pujiastuti et al., 2022). The final adhesive is tar, particularly the tar produced from biomass processing (biotar). This type of tar is generated in significant quantities during thermochemical processes and consists of a mixture of various compounds that are difficult to separate. Therefore, the use of tar as a bio-briquette adhesive offers considerable advantages (Ngene et al., 2024). Tar, which is an organic-hydrophobic adhesive, has been applied in the production of bio-briquettes made from areca nut shells (Muddin, 2019), sengon wood sawdust (Musyono et al., 2020), as well as a mixture of organic waste and jatropha seed cake (Kurniawan et al., 2012).

In addition to the type and concentration of adhesive, another variable that significantly affects the quality of bio-briquettes is the size of the bio-char particles used. Particle size greatly influences the compressibility of the raw material, as well as the physical, mechanical, durability, and combustion characteristics of the bio-briquettes (Gürdil and Demirel, 2018). Biomass must be ground into smaller or appropriate particle sizes to enhance the surface area-to-volume ratio, which subsequently improves the mechanical interlocking between particles during the densification or compaction process (Demisu and Muluye, 2024). The same principle also applies during the refinement stage of bio-char prior to the briquetting process.

The selection of optimal operating conditions in bio-briquette production can be carried out using the analytical hierarchy process (AHP) method. AHP is a multi-criteria decision-making tool that has been widely applied to decision-making processes across various fields (Vaidya and Kumar, 2006). In the AHP method, several alternative options are evaluated by assigning scores to each based on selected criteria, followed by the calculation of a final average score. These alternatives are then ranked according to their final scores, with the highest score indicating the most preferred option after considering key parameters. AHP has been extensively utilized in decision-making processes across diverse problem domains. In this study, an investigation was conducted to assess the reliability of AHP in selecting the operating conditions for bio-briquette production, considering that this specific application has received limited attention in previous research.

Candlenut shells constiute one of the biomass resources that can be utilized for bio-briquette production. Candlenut is one of Indonesia's abundant natural resources with broad market prospects, both domestically and internationally (Sulhatun et al., 2018). Candlenut (*Aleurites moluccana*) belongs to the *Euphorbiaceae* family, thrives well in tropical regions, and has been widely utilized in various agro-industrial activities. Inevitably, the processing of candlenut generates candlenut shells waste, which remains underutilized. Candlenut shells waste is classified as organic waste with a hard texture (Hamid et al., 2024). This waste, derived from candlenut seed processing activities, contains high carbon content, making it suitable for bio-char production. Therefore, the utilization of candlenut shells as bio-char offers a sustainable approach to waste management while contributing to environmental quality improvement (Dethan, 2024).

On the basis of this background, this study aimed to select the optimal operating conditions, including the adhesive type, adhesive concentration, and bio-char particle size for the bio-briquettes fabrication from candlenut shells. The selection process was conducted gradually based on key parameters, such as moisture content, ash content, and bio-briquette density. The best variable from each stage was applied to the next stage while simultaneously evaluating other operating conditions. Once the optimal bio-briquette formulation was identified, further characterization was performed to assess its performance, including compressive strength, volatile matter content, fixed carbon content, calorific value, and combustion rate. To the best of authors' knowledge, such a comprehensive investigation (especially using candlenut shell biomass) has not been previously reported, making this study novel. Furthermore, this work highlights the potential of candlenut shell biomass as an affordable and accessible renewable energy source.

MATERIALS AND METHOD

Materials and equipment

The main materials used in this study include candlenut shells, tapioca starch, molasses, tar, and water. The candlenut shells, serving as the biomass feedstock for bio-briquette production, were sourced from Sumatera Utara Province, Indonesia. Starch was purchased from local vendors in Medan, Indonesia. Molasses was obtained from a sugar factory located in Sumatera Utara, Indonesia. Meanwhile, the tar was derived from the pyrolysis process of the candlenut shells themselves. The bio-char production from candlenut shells was carried out using a pyrolysis reactor, as illustrated in Figure 1. Other supporting equipment included a digital balance, oven, desiccator, mortar and pestle, sieves with mesh sizes of 20, 40, and 80, a bio-briquette molding machine, a bomb calorimeter, and various glassware.

Pyrolysis procedure

A total of 2 kg of candlenut shells were dried using open-sun drying for approximately one day, followed by moisture content analysis prior

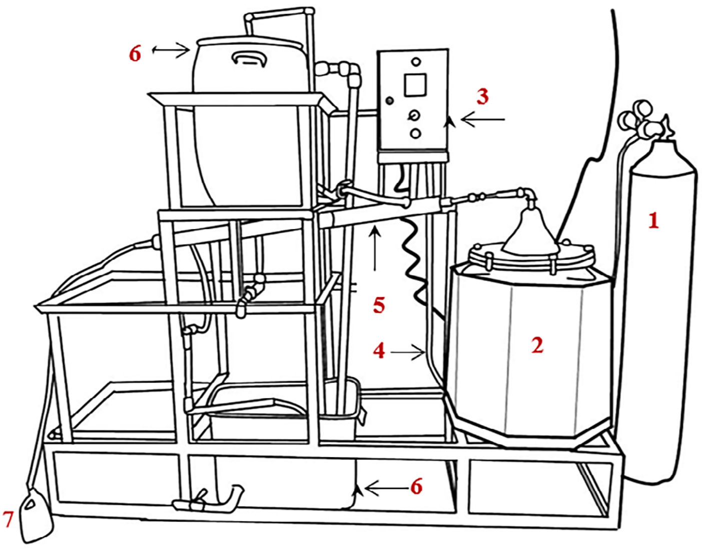

Figure 1. The schematic of pyrolysis reactor: (1) N_2-tank; (2) pyrolysis reactor; (3) thermocouple; (4) thermocouple wire; (5) condenser; (6) cooling water; (7) Tar collecting tank

to carbonization. The dried candlenut shells were subjected to pyrolysis at a temperature of 350 °C for 4 hours. After the pyrolysis process was completed, the resulting bio-char was spread onto a metal plate and left to cool until both the smoke and residual heat dissipated. The bio-char was ground and sieved to obtain uniform particle sizes using sieves with mesh sizes of 20, 40, and 80 mesh.

Bio-briquettes production

The production of bio-briquettes began by varying the type of adhesive, namely starch, molasses, and tar, to determine the most suitable adhesive. A total of 30 g of candlenut shell bio-char with a particle size of 80 mesh was mixed with each type of adhesive, with an adhesive concentration of 30% (w/w) relative to the mass of bio-char used. For starch adhesive, the tapioca flour was dissolved in water at a tapioca-to-water ratio of 1:10 (w/v). The mixtures were molded using a bio-briquette molding machine. The resulting bio-briquettes were oven-dried at 100 °C for 30 minutes. The second stage involved selecting the optimal adhesive concentration based on the best adhesive identified in the previous stage. At this stage, 30 g of 80-mesh candlenut shell bio-char was mixed with the selected adhesive at concentrations of 10%, 20%, and 30% (w/w). The final stage was the selection of the optimal biochar particle size based on the best type and concentration of adhesive. At this stage, the bio-char particle sizes used were 20, 40, and 80 mesh. In each stage, the quality of the bio-briquettes was evaluated in triplicate based on moisture content (ASTM D 5142-02), ash content (ASTM D 5142-02), and density (ASTM D 5142-02). The best bio-briquette obtained from the final stage was subjected to further characterization, including compressive strength, volatile matter content, fixed carbon content, calorific value, and burning rate. The bio-briquette characteristics were also compared with the Indonesian National Standard (SNI) No. 01-6235-2000 (BSN, 2020), as well as other relevant standards such as ISO 17225-1:2020 (ISO, 2020) and standards from other countries.

The selection of the optimal variables at each stage was carried out using the AHP method. In this study, the criteria used were moisture content (C1), ash content (C2), and density (C3). The standard preference scale used for AHP is presented in Table 1, which was established by experienced researchers in the application of AHP.

Table 1. Preference scale for AHP (Taylor, 2013)

Preference level	Numeric value
Equally preferred	1
Equally to moderately preferred	2
Moderately preferred	3
Moderately to strongly preferred	4
Strongly preferred	5
Strongly to very strongly preferred	6
Very strongly preferred	7
Very strongly to extremely preferred	8
Extremely preferred	9

RESULTS AND DISCUSSION

Stage I: selection of adhesive

Stage I involved selecting the best adhesive among tapioca, molasses, and tar. In this stage, bio-briquettes were produced using an adhesive concentration of 30% and a biochar particle size of 80 mesh. The moisture content, ash content, as well as density of bio-briquettes made with tapioca, molasses, and tar adhesives are presented in Figure 2.

Moisture content is one of the key parameters in determining the quality of bio-briquettes. Essentially, the water content in biomass assists in the briquette formation process by facilitating the agglomeration between particles and activating the natural adhesives present in the biomass. However, excessive moisture content causes a portion of the energy that should be used for combustion to be diverted toward evaporating the moisture within the biomass (Granado et al., 2021). In addition, high moisture content leads to the formation of smoke during the combustion of bio-briquettes (Yirijor and Bere, 2024). As shown in Figure 2, the moisture content of bio-briquettes was recorded at 1.50% for those made with starch adhesive, 2.90% with molasses, and 3.80% with tar. The moisture content of each adhesive contributed to the final moisture content of the produced bio-briquettes. Starch adhesive resulted in the bio-briquettes with the lowest moisture content, considering that starch itself has a relatively low moisture content of approximately 12.9% (Milya et al., 2023). All bio-briquettes produced in Stage I met the moisture content requirements set by the SNI, which stipulates a maximum of 8%, as well as ISO 17225 standards, which classify moisture content at ≤

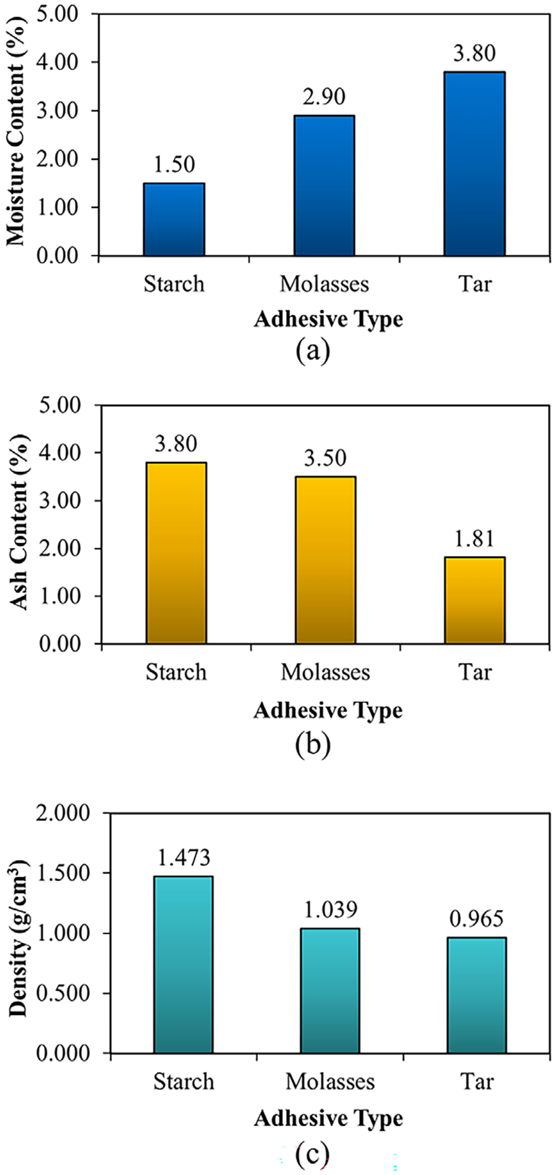

Figure 2. (a) Moisture content; (b) ash content; (c) and density of bio-briquettes at various adhesive types

10% as M10. Ash content refers to the percentage of non-combustible material remaining after the combustion of bio-briquettes (Sanchez et al., 2022). The ash content of bio-briquettes in Stage I was 3.80% for those made with starch, 3.50% with molasses, and 1.81% with tar. The fuels with high ash content generally exhibit lower calorific value and slower combustion rates (Onukak et al., 2017). All bio-briquettes produced in Stage I met the ash content requirements stipulated by the SNI, which sets a maximum limit of 8%. In addition, these bio-briquettes also complied with other standards, such as ISO 17225 (≤ 5.0%, classified as A5.0), the Japanese bio-briquette standard (3.0–6.0%), and the Thai Community Quality Standard (657/2547), which sets a maximum ash content of 10% (Ifa et al., 2020).

Density is an essential quality parameter as it serves as an indicator for other performance attributes. Generally, the briquettes with higher density exhibit better overall performance compared to those with lower density (Yunusa et al., 2024). The bio-briquettes produced in Stage I had densities of 1.473 g/cm^3, 1.039 g/cm^3, and 0.965 g/cm^3 for starch, molasses, and tar adhesives, respectively. These density values are also consistent with authors' previous investigation using coffee stem bio-char under the same pyrolysis temperature (350 °C), which resulted in bio-briquette densities of 1.34 g/cm^3 for tapioca adhesive and 1.21 g/cm^3 for molasses adhesive (Hasibuan et al., 2024).

In the selection of adhesives for commercial bio-briquette production, the influence of adhesive type and quantity on the characteristics of bio-briquettes is crucial to investigate. Adhesive selection is often influenced by factors such as availability, cost, raw material properties, moisture content of the mixture, densification pressure, and the desired energy content of the briquettes. In most developing communities, the cost and availability of adhesives become the most important factors in adhesive selection (Obi et al., 2022).

The results of the AHP analysis in Table 2 indicate that starch is the best adhesive, with the highest average score (0.4693). In the AHP method, decisions are made by evaluating the final scores of each alternative. The option with the highest final score is considered the most preferred, based on key parameters. As summarized in Table 2, the highest average score was achieved using starch-based adhesive, followed by molasses and tar. This indicates that starch is the most preferred and suitable adhesive for the production of the bio-briquettes derived from candlenut shell charcoal, considering the resulting moisture content, ash content, and briquette density.

The use of starch adhesive produces the bio-briquettes with low moisture content but high density, making the bio-briquettes less prone to breakage. Its high energy content, along with favorable chemical and structural properties, makes starch a superior adhesive for biomass densification processes and the most widely used adhesive in various studies (Obi et al., 2022). Furthermore, a review conducted by Ngene et al. (Ngene et al., 2024) also highlighted that starch offers strong adhesion properties, although with relatively low

Table 2. Final scores on the adhesive selection stage

Adhesives	C1	C2	C3	Average score
Starch	0.4932	0.4429	0.4720	0.4693
Molasses	0.3682	0.3873	0.3767	0.3774
Tar	0.1386	0.1698	0.1513	0.1533

water resistance. On the other hand, molasses provides good adhesion and calorific value, but can increase the moisture absorption tendency of bio-briquettes. Meanwhile, tar is a low-cost adhesive classified as a type II-adhesive, derived from the by-products of lignocellulosic biorefinery processes. The use of tar aims to utilize the by-products that have not yet been optimally valorized. However, the application of tar as an adhesive in bio-briquette production poses environmental concerns due to the potential release of volatile matter, particulate matter, as well as SO_2 and NOx emissions. Cong et al. (2021) stated that the use of tar remains feasible through a co-densification approach. In this context, bio-tar functions as an effective lubricant and binder in the densification process due to its high viscosity. This viscosity can be reduced, and its flowability improved, by adjusting the temperature within an optimal range of 35–50 °C. Therefore, the studies concerning the use of tar as a binding agent should be accompanied by the determination of an appropriate densification temperature to ensure process efficiency.

Stage II: selection of adhesive concentration

The second stage is the selection of the optimal adhesive concentration. Fundamentally, there is no fixed or universally optimal composition of the adhesive for bio-briquette production. Although the adhesive significantly influences the quality of the bio-briquettes, other factors also play crucial roles, such as the type of biomass, particle size, compressive strength, and others. In this study, binder concentrations of 10%, 20%, and 30% were selected, as this concentration range is commonly used in various previous studies. Figure 3 presents the moisture content, ash content, and density of bio-briquettes at various adhesive concentrations. The resulting moisture content was 4.90% at 10% adhesive concentration, 4.00% at 20%, and 1.50% at 30%. All the bio-briquettes produced in Stage II still met the moisture content limits required by SNI (max. 8%) and ISO 17225 (≤ 10%). In terms of ash content, starch gave the ash contents ranging from 2.00% to 3.80%, all of which still met the limits set by SNI (max. 8%), ISO 17225 (≤ 5.0%), the Japanese bio-briquette standard (3.0–6.0%), and the Thai Community Quality Standard (657/2547) (max. 10%) (Ifa et al., 2020). Finally, density analysis revealed an increasing trend in bio-briquette density, from 0.870 g/cm^3 at 10% adhesive concentration to

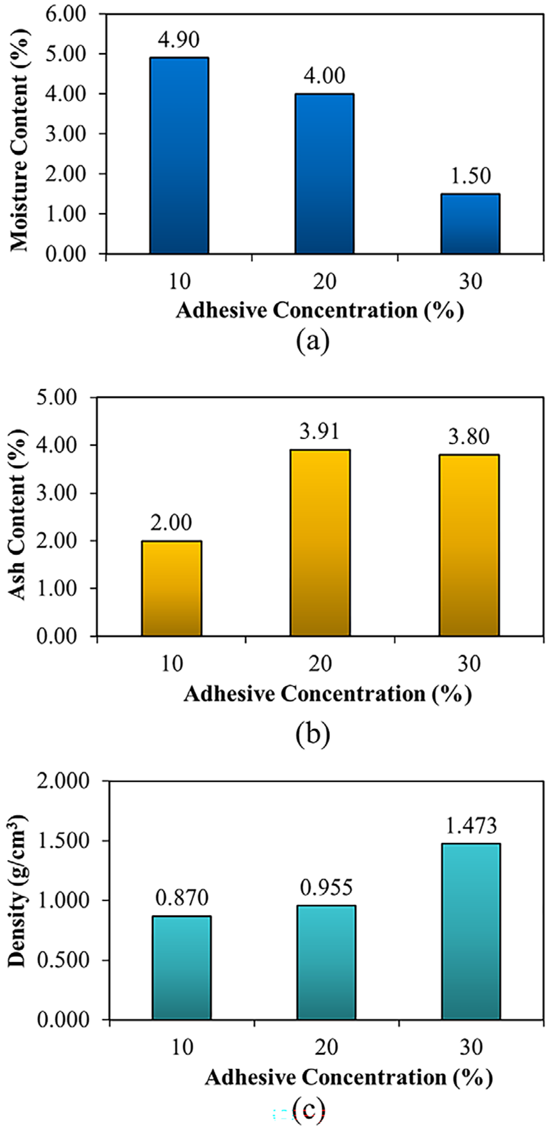

Figure 3. (a) Moisture content; (b) ash content; (c) and density of bio-briquettes at various adhesive concentrations

1.473 g/cm^3 at 30%. This trend suggests that higher adhesive concentrations enhance particle binding, resulting in denser bio-briquettes.

The AHP analysis revealed that a 30% adhesive concentration is the optimal composition for producing bio-briquettes from candlenut shells. This conclusion is based on the final average scores obtained, where the 30% adhesive concentration achieved the highest score (0.4791), followed by 20% (0.3023) and 10% (0.2186). In other words, a 30% adhesive concentration yielded the most favorable (i.e., most preferred) bio-briquette characteristics among the tested concentrations, based on key parameters such as moisture content, ash content, and briquette density. Increasing the adhesive concentration contributes to a higher percentage of non-combustible material, which in turn increases the ash content of the bio-briquettes. As it was mentioned, ash refers to the residue of non-combustible material left after the bio-briquette is burned. Ash is predominantly composed of silica minerals, and high ash content can reduce the calorific value of the bio-briquette, ultimately lowering its overall quality. However, the increase in adhesive concentration also enhances the density of the bio-briquette, improving its structural integrity and prolonging its burning duration. Consequently, this contributes to an increase in the overall calorific value of the bio-briquette, balancing the negative impact of increased ash content (Jayana and Theresia, 2022) (Table 3).

Stage III: selection of bio-char particle size

The final stage in investigating the effect of operating variables on the quality of bio-briquettes is the selection of the particle size of candlenut shell charcoal. Bio-char powder with particle sizes of 20 mesh, 40 mesh, and 80 mesh was used to produce bio-briquettes using tapioca adhesive with an adhesive concentration of 30%. Figure 4 visualizes the moisture content, ash content, and density of the bio-briquettes in this third stage. The moisture content of the bio-briquettes was 5.00% for 20-mesh biochar, 5.70% for 40-mesh biochar, and 1.50% for 80-mesh bio-char. These bio-briquettes also met the moisture content limits set by SNI (max. 8%) and ISO 17225 (≤ 10%). Furthermore, the use of bio-char with particle sizes of 20, 40, and 80 mesh resulted in the bio-briquettes with ash contents of 4.05%, 3.20%, and 3.80%, respectively. These values also meet the standards set by SNI

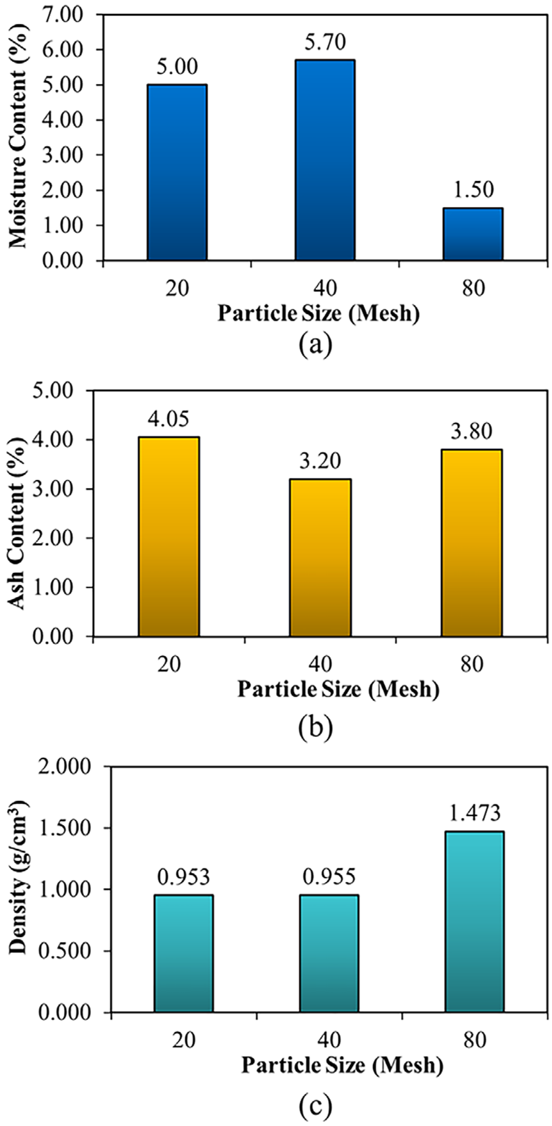

Figure 4. (a) Moisture content; (b) ash content; (c) and density of bio-briquettes at various biochar particle sizes

Table 3. Final scores on the adhesive concentration selection stage

Adhesive concentrations	C1	C2	C3	Average scores
10%	0.2632	0.2333	0.1593	0.2186
20%	0.2884	0.3667	0.2519	0.3023
30%	0.4484	0.4000	0.5889	0.4791

(max. 8%), ISO 17225 (≤ 5.0%), the Japanese bio-briquette standard (3.0–6.0%), and the Thai Community Quality Standard (657/2547) (max. 10%) (Ifa et al., 2020). Finally, the density of the bio-briquettes produced, as shown in Figure 4, was 0.953 g/cm^3, 0.955 g/cm^3, and 1.473 g/cm^3. The increase in bio-briquette density when using finer biomass particles was also reported by Gill et al. (Gill et al., 2018) in the production of bio-briquettes from rice straw powder.

The AHP method identified 80 mesh as the optimal particle size of bio-char, with an average score of 1.8847 (Table 4). This score was higher than that of 40 mesh (0.7878) and 20 mesh (0.4747), indicating that the 80-mesh particle size produced bio-briquettes with the most favorable key parameters and was the most preferred among the tested sizes. The particle size of the raw material affects the density of the bio-briquettes. Furthermore, the density of the bio-briquettes influences other characteristics, such as compressive strength, burning duration, and ease of ignition. Ideally, bio-briquettes should not have excessively high density to allow sufficient oxygen flow through the internal pores during combustion (Sunardi et al., 2019). The strength properties of briquettes, such as density and durability, are inversely related to particle size, as smaller particles provide a larger contact surface area during the densification process (Waheed et al., 2022). Finer particles create fewer pores but provide greater material mass per unit volume, which is beneficial for the briquette formation process (Oladeji and Enweremadu, 2012).

Characteristics of bio-briquettes under optimum conditions

The utilization of bio-briquettes is expected to help reduce pollution problems while also serving as an energy source for industries. Bio-briquettes can be used for household purposes such as cooking, heating, grilling, as well as for industrial needs, including agroindustrial applications or food processing in both urban and rural areas (Maulina et al., 2019). A series of evaluations conducted in this study concluded that the optimal bio-briquette was produced using tapioca adhesive, with an adhesive concentration of 30% and a biochar particle size of 80 mesh. Furthermore, additional characterizations were carried out to evaluate the performance of the resulting bio-briquettes.

The characteristics of the bio-briquettes in this study are summarized in Table 5. In addition, a comparison of the characteristics of bio-briquettes made from various types of biomass using tapioca adhesive, obtained from previous studies were presented. On the basis of Table 5, it is evident that only the presented study conducted a comprehensive characterization to evaluate the quality of the bio-briquettes. The moisture content of the bio-briquettes in this study was also the lowest. On the other hand, the calorific value was the highest, even exceeding the threshold requirements of both SNI and ISO standards, making it a key advantage of this research. In authors' previous investigation (Hasibuan et al., 2024), bio-briquettes made from coffee stem charcoal also demonstrated satisfactory characteristics, with very promising calorific values. A series of evaluations confirmed that the bio-briquettes made from candlenut shell charcoal in this study have excellent quality and strong potential to be applied as an alternative energy source in rural areas.

Limitation and future perspective

In this study, the selection of optimal operating conditions for the production of bio-briquettes derived from candlenut shell bio-char was carried out. The AHP method was systematically applied to determine the most suitable adhesive type, adhesive concentration, and biochar particle size, using moisture content, ash content, and bio-briquette density as key evaluation parameters. However, it must be acknowledged that this study has certain limitations. Notably, the optimal compressive strength for bio-briquette formation was not evaluated, nor was the influence of initial bio-char moisture content on briquette quality explored. These aspects are worth considering, as

Table 4. Final scores on the bio-char particle sizes selection stage

Bio-char particle sizes	C1	C2	C3	Average scores
20 mesh	0.2632	0.1638	1.0000	0.4757
40 mesh	0.2884	0.2973	1.7778	0.7878
80 mesh	0.4484	0.5390	4.6667	1.8847

Table 5. Characteristics of various bio-briquettes using tapioca adhesive

Biomass	MC (%)	AC (%)	Density (g/cm^3)	Compressive strength (kg/cm^2)	VM (%)	FC (%)	BR (g/min)	CV (cal/g)	Ref.
Candlenut shells	1.50	3.80	1.473	36.86	18.00	77.00	0.018	8254.25	This work
Coffe stem	2.45	2.35	1.345	91.76	1.24	-	-	7463.96	(Hasibuan et al., 2024)
Sewadge sludge+wood shavings	-	-	-	-	-	-	10.51	2507.88	(Oduro et al., 2024)
Rubber fruit shells+wood twigs	4.50	2.19	2.250	-	13.73	-	-	6653.60	(Iriany et al., 2023)
Rice husk+jengkol peel	2.00	2.00	-	-	-	96.00	-	5576.34	(Tambun et al., 2024)
Coconut shells+LDPE	15.12	18.77	-	-	48.00	18.11	-	4755.83	(Anggita et al., 2023)
Coconut husk+LDPE	17.08	19.33	-	-	44.00	19.59	-	4486.97	
Coconut shells+coconut husk+LDPE	12.93	15.65	-	-	42.00	29.42	-	4730.31	
Pineapple peel	5.00	11.00	-	-	13.00	76.00	-	4753.99	(Ariani et al., 2023)
Meranti wood	31.27	2.42	-	-	55.07	-	-	4388.36	(Vegatama and Sarungu, 2022)
Coconut shells	10.58	11.03	-	-	30.01	48.38	-	6564.88	(Yerizam et al., 2021)
Areca fiber	-	-	0.319	-	-	-	-	2950.44	(Hasanuddin et al., 2020)
Kenari shells	4.30	12.85	-	-	27.00	55.90	-	-	(Sundari et al., 2019)
Filicium decipiens leaves	6.13	14.73	-	-	35.84	43.3	-	5236	(Nurhilal et al., 2018)
Samanea saman leaves	7.26	13.57	-	-	29.85	49.32	-	5126	
Mahogany leaves	6.51	13.96	-	-	35.15	44.38	-	5055	
SNI No. 01-6235-2000	Max. 8	Max. 8	-	-	Max. 15	-	-	Min. 5000	(BSN, 2020)
ISO 17225	0–15	0–10	-	-	-	-	-	Min. 4302.1	(ISO, 2020)
Japanese bio-briquette standard	-	3.0–6.0	-	-	15–30	60.0–80.0	-	-	(Ifa et al., 2020)
Thai Community Quality Standards (657/2547)	-	Max. 10	-	-	-	-	-	-	(Ifa et al., 2020)

Note: MC – moisture content; AC – ash content; VM – volatile matter; FC – fixed carbon, BR – burning rat; CV – calorific value.

both compressive strength and initial moisture content are important variables – beyond those studied in this work – that significantly affect the overall quality of bio-briquettes.

Nonetheless, this paper has successfully demonstrated the characteristics of the produced bio-briquettes and compared their quality with similar studies, as summarized in Table 5. The best-performing bio-briquette in this study was produced using starch as an adhesive, with a 30% adhesive concentration and 80 mesh charcoal particle size. This bio-briquette exhibited outstanding properties, particularly in terms of calorific value, when compared to 15 other studies listed in Table 5. For long-term development, several aspects remain to be explored to further support the potential utilization of candlenut shell-based bio-briquettes as an accessible renewable energy source. Emission studies, life-cycle assessments (LCA), and economic analyses could be conducted by future researchers. Finally, evaluating the performance of these bio-briquettes at an industrial scale – such as their application in boilers or heating systems – should also be considered to validate their potential as a more environmentally friendly renewable energy alternative.

CONCLUSIONS

The production and characterization of candlenut shell-based bio-briquettes were carried out by investigating the types of adhesives, adhesive concentrations, and biochar particle sizes used. Analysis using the AHP was conducted systematically to determine the optimal operating conditions for bio-briquette production. The best bio-briquette was obtained using starch adhesive, with an adhesive concentration of 30% and a biochar particle size of 80 mesh. Under these conditions, the resulting bio-briquette had a moisture content of 1.50%, ash content of 3.80%, density of 1.473 g/cm^3, compressive strength of 36.86 kg/cm^2, volatile matter content of 18.00%, fixed carbon content of 77.00%, burning rate of 0.0018 g/min, and a calorific value of 8254.25 cal/g. Overall, the quality of the produced bio-briquettes met the standards of SNI No. 01-6235-2000, ISO 17225, and other international standards. Interestingly, the bio-briquette produced under these conditions exhibited an exceptionally high calorific value, surpassing several other bio-briquettes compared in this study. The success of the AHP method in selecting the operating conditions for bio-briquette production has demonstrated its effectiveness in addressing the issues in the energy and waste management sectors, where AHP has yet to be widely applied. This study offers a high-quality bio-briquette product that is highly suitable for use by the community, particularly in rural areas, as an affordable, environmentally friendly, and sustainable alternative energy source.

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