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Research article

From Waste to Energy: Optimizing Briquette Properties from Sago Palm Residue with Glycerin Binder

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Abstract

This research investigated the effects of carbonization temperature (from 300°C to 500°C) and glycerin content (from 0.00% to 60.00% by weight) on the physical and thermal properties of briquette produced from sago palm residue. The results revealed that increasing both the carbonization temperature and glycerin content enhanced the physical properties of the briquettes—particularly the shatter index (%shatter index) and durability ($\%D_r$)—mainly due to greater densification. This enhancement led to superior briquette because glycerin helped to increase bulk density and reduce void spaces between particles. Both glycerin content and carbonization temperature had positive effects on thermal properties. Briquette produced by carbonizing sago palm residue at 400°C with 60.00% glycerin exhibited the best thermal characteristics, with the highest heating value and energy density of 22.15 MJ/kg and 12,847 MJ/m^3, respectively. This was because the proportions of combustible components—fixed carbon (FC) and volatile matter (VM)—were 1.04 times higher than those of briquettes produced by carbonizing the sago palm residue at 300°C and 500°C with 60.00% glycerin. Higher combustible components resulted in greater energy output, which was reflected in the lower fuel consumption needed when boiling 20.00 mL of water. The consumption of briquettes produced by carbonizing sago palm residue at 400°C was 33.90% and 19.95% less than briquettes produced by carbonizing sago palm residue at 300°C and 500°C, respectively (12.83 g for 300°C). In accordance with the maximum energy-mass co-benefit index (EMCI) of 15.52, the optimum carbonization temperature for producing effective briquettes from sago palm residue was 400°C.

Keywords: sago palm residues; glycerin; briquette; carbonization; physical property; thermal property

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1. Introduction

Currently, global energy consumption continues to rise every year, while energy resources remain limited. In 2024, global energy demand grew by 2.20%, a rate significantly higher than the annual average of 1.30% observed between 2013 and 2023 (International Energy Agency, 2023). Approximately 80.00 % of the world's primary energy usage is derived from fossil fuels including coal, oil, and natural gas. This is because fossil fuel technologies have benefited from decades of investment in mining, drilling, transportation, and power generation infrastructure. This well-established network ensures reliable energy distribution with relatively low operational complexity (International Energy Agency, 2025). Since fossil fuels provide a large amount of energy per unit of mass or volume, they are appropriate for heavy industries, long-distance transportation, and aviation—all of which depend heavily on energy efficiency. Even though the utilization of fossil fuels has many advantages, it remains the biggest source of greenhouse gas emissions (primarily carbon dioxide), globally. Interestingly, the Intergovernmental Panel on Climate Change (IPCC) indicates that the burning of fossil fuels is responsible for about 75.00% of global CO_2 emissions. These emissions contribute directly to environmental problems such as global warming, ocean acidification as well as long-term climate instability. Both the fast rise of energy demand and environmental problems associated with fossil fuel usage have driven the search for alternative energy sources (Lv, 2023). It is widely recognized that fossil fuels are non-renewable resources that are being depleted at an unsustainable rate. Therefore, alternative energy sources have been considered in an effort to facilitate a more sustainable energy transition and reduce dependency on fossil fuels.

Biomass-based renewable energy is considered more environmentally friendly and capable of meeting long-term human energy needs (Ali et al., 2024). The primary source of biomass energy is organic material such as agricultural residue, animal manure, and industrial waste, and examples include rice straw, bagasse, food waste, cassava residue, and sago palm residue (Guo et al., 2024). All of those materials are typically disposed of through open burning or landfilling—practices that cause environmental concerns (Mehmood et al., 2022). Utilizing these organic wastes as sources of energy could significantly reduce the dependence on fossil fuels and contribute to a reduction in environmental issues. This is owing to the fact that organic waste can provide energy efficiency comparable to, or even surpassing, that of fossil fuels. Additionally, the burning of biomass only releases CO_2 that the plants can absorb and utilize for growth, making it technically carbon neutral. On the other hand, carbon that has been held for millions of years is released by fossil fuel combustion. As a result, biomass is a sustainable and renewable energy source due to its capability to be regenerated within a short cycle, unlike fossil fuels, which take millions of years to form. Furthermore, the use of biomass as an energy source can support the waste management that is in alignment with the principles of circular economy. Consequently, the use of biomass in the form of briquette fuel has gained increasing attention due to its sustainability, low investment and high energy source performance. From the earlier research work, briquettes produced from durian shells and sugarcane bagasse with glycerin as a binder exhibited 75.00% improvement in mechanical and thermal properties when compared with briquettes without glycerin (Asavatesanupap & Malee, 2010). Similarly, food waste-based briquettes that were mixed with molasses showed improvements in their mechanical properties, demonstrating higher density and excellent compressive strength and impact resistance. Waste glycerin, a byproduct of biodiesel production, exhibits a high energy content of 20.73 MJ/kg. Consequently, its calorific heating value was approximately 17.39% higher than that of the other binders

reported by Asavatesanupap and Malee (2010). This research was motivated by the promise of using waste glycerin as a binder to enhance the physical and thermal characteristics of briquettes produced from sago palm residue. The waste glycerin content under investigation ranged from 0.00% to 60.00% by weight. According to the hypothesis, adding waste glycerin might be beneficial for enhancing both physical and thermal properties.

Sago palm is an economically important crop in the southern region of Thailand, with a variety of uses. The sago palm's starch-rich trunk is processed to extract starch, a process that leaves behind a substantial amount of waste that includes the outer bark and sludge. Both the outer bark and sludge contain a high moisture content (over 40.00% by weight), and the materials if not inadequately managed, become a breeding ground for diseases and cause environmental problems, including the generation of unpleasant odors (Amin et al., 2019). Researchers have therefore looked at utilizing sago palm residue in various kinds of industries, for example animal feed and/or energy source (Jariyapong et al., 2023; Imram et al., 2025). Nevertheless, in case of using sago palm residue as an energy source, its direct burning contributes to environmental pollution, e.g., acid rain, global warming, and smog issues, by releasing harmful gases like sulfur dioxide (SO_2) and carbon dioxide (CO_2). To mitigate these environmental impacts, employing sago palm residue to produce briquette was examined. The briquettes produced for this study were first carbonized at different carbonization temperatures ranging from 300°C to 500°C with limited oxygen present. Physical and thermal characteristics were explored in a cylindrical form with a diameter of 30 mm and a thickness of 9 mm.

2. Materials and Methods

2.1 Sago palm residue preparation

The sago palm residue used in this research was sourced from Yai Chui's plantation, located in Khuan Khanun, Phatthalung, Thailand. The collected sago palm residue was sun-dried for 7 days to reduce moisture and/or water content. After drying, the sago palm residue was ground by using a mechanical blender to reduce its particle size, and subsequently sieved through a 60-mesh screen to ensure uniform and sufficiently fine particle size ($\approx$ 250 μm). A 60-mesh sieve was employed based on earlier research by Hakim et al. (2025), who indicated that smaller particle sizes offered a larger surface area and may improve the carbonization behavior of sago palm residue. The resulting powder was stored in a desiccator to prevent moisture absorption before further use.

2.2 Conversion of sago palm residue into charcoal

The fine sago palm residue powder sieved through a 60-mesh screen was subjected to carbonization process at temperatures of 300°C, 400°C, and 500°C, with heating rate of 5°C/min for 1 h. For the carbonization of sago palm residue, a fixed-bed (batch) reactor was employed under air free atmosphere. This type of reactor is widely used in laboratory-scale biomass carbonization studies because of its simplicity and ease of control (Tumuluru et al., 2021). Thus, by selecting 300°C, 400°C and 500°C, a sensible range of carbonization conditions—from low, intermediate to higher temperatures— was covered. This choice enabled the comparison of fuel characteristics, carbon yields and binder/structural interactions across a meaningful temperature range. The carbonization process yielded charcoal, which ranged in color from reddish-brown to black, depending on the

carbonization temperature. The charcoal was sieved through a 60-mesh screen in order to maintain the particle size. The 60-mesh screening was shown to enhance densification, improve packing of particles, promote binder penetration, reduce internal voids and thus increase briquette density and mechanical strength (Hakim et al., 2025). The resulting fine chacoal powder was analyzed for proximate composition and ultimate composition. The proximate composition was examined in accordance with the Chinese national standard for proximate analysis of solid fuels (GB/T 28731-2012), following the procedure outlined in a previous study by Lohani et al. (2024) and Zhai et al. (2018). While the ultimate composition was estimated by CHNS analyzer (CHNS-LECO/CHN628, CHN628S, USA).

2.3 Briquette fuel production

The briquettes were prepared by blending fine charcoal powder, obtained from carbonization process at the temperatures of 300°C, 400°C, and 500°C, with glycerin at ratios ranging from 0.00% to 60.00% by weight. After the mixtures for each specified ratio was obtained, the blended materials were compressed using a hydraulic press under a pressure of 20.00 MPa to form cylindrical briquettes. Each briquette had a diameter of 30.00 mm and a thickness of 9.00 mm (as shown in Figure 1).



Figure 1. (A) The neat sago palm residue prior to the carbonization process and the briquettes produced from carbonized sago palm residue at (B) 300°C, (C) 400°C and (D) 500°C

2.4 Physical and thermal properties analysis

The physical properties of the briquettes were evaluated in terms of shatter capability (% shatter index), durability (D_r), densification, and mass yield ratio (η_M), following standard methods for solid fuel testing as described in previous studies (Altıkat et al., 2024; Mueanmas & Rakmak, 2024; Ngene et al., 2024). For the thermal properties, the heating values of the briquette fuel were determined using a bomb calorimeter (IKA® Calorimeter System C5000 control, Germany). Meanwhile, the energy yield ratio (η_E) and energy density were measured according to the solid fuel testing standards reported in earlier research (Qian et al., 2017; Mueanmas & Rakmak, 2024). All tests were conducted using five briquette samples per each ratio of glycerin content and each carbonization temperature. The testing conditions for both physical and thermal properties were maintained at standard ambient conditions: a temperature of 30°C and relative humidity of 60.00-65.00%. Data variability was analyzed using the standard deviation method, with a confidence level of 95.00%. Furthermore, the combustion efficiency evaluation of briquettes was conducted using the boiling-water test. A fixed volume of 20.00 mL of water was heated in a glass beaker placed above the briquette flame. The choice of 20.00 mL

was based on preliminary trials to match the thermal load with the small briquette mass (≈ 5.00 g), ensuring a measurable temperature rise within a short testing time while avoiding complete evaporation.

3. Results and Discussion

3.1 Physical properties of briquette

3.1.1 Shatter capability and durability

The mechanical properties of the briquettes were represented by the shatter capability (% shatter index) and durability (% D_r), which are defined in equations 1 and 2, respectively (Sengar et al., 2012; Wang et al., 2017). The % shatter index is a significant parameter for evaluating the mechanical characteristic of solid fuels during production, handling, transportation, and end-use (Ibitoye et al., 2022). Both % D_r and % shatter index might also be used for designing transport and storage systems. Fragile fuels require controlled conveying mechanisms to avoid deterioration (Elsisi et al., 2025). In this research, both the % shatter index and the % D_r of the studied briquettes increased with increasing carbonization temperatures from 300°C to 500°C. A similar trend appeared for the % shatter index and the % D_r of the studied briquettes with added glycerin; these 2 parameters improved as the glycerin content rose. When briquettes were produced under the carbonization temperature of 400°C and 500°C with added glycerin at the maximum ratio of 60.00% by weight, the highest % shatter index and the maximum % D_r were achieved. The maximum of both % shatter index and % D_r exceeded 99.00% as illustrated in Figure 2. These values were considered acceptable as they surpassed the values of the commercial biochar and biomass briquettes that had shatter indexes and durability values of approximately 95.00-99.00% and 70.00-95.00%, respectively, depending on raw material and binder type (Ngene et al., 2024) (Table 1). Moreover, the mechanical properties of this briquette investigated in this study were superior to those of industrial charcoal briquettes, as evidenced by a 18.82-19.64% higher shatter index. It demonstrated that the studied briquettes were exceptionally robust and were well-suited for automated fueling systems in boilers and stoves (Kebede et al., 2022) (Table 1).

$$\%\ shatter\ index = \frac{w_f - w_i}{w_i} \times 100 \quad (1)$$

$$\%\ D_r = \frac{w_{f_D}}{w_{i_d}} \times 100 \quad (2)$$

Where:

w_f is the briquette sample weight after vertical drop from a height of 1.00 m onto concrete surface (g).

w_i is the briquette sample weight before vertical drop from a height of 1.00 m onto concrete surface (g).

w_{f_D} is the briquette sample weight after vertical drop from a height of 1.50 m onto metal surface (g).

w_{i_D} is the briquette sample weight before vertical drop from a height of 1.00 m onto metal surface (g).

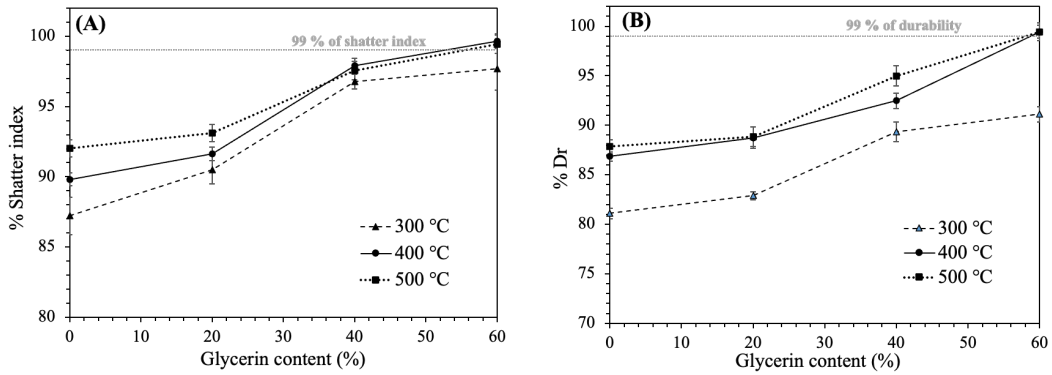


Figure 2. (A) % shatter index and (B) % durability (%Dr) of briquettes produced from sago palm residue at different carbonization temperatures and different glycerin content

Table 1. The comparison of mechanical properties of various types of briquettes

Briquette Type	Durability (D_r) (%)	Shatter Index (%)	Ref.
Sago palm residue	>99.00	>99.00	This study
Cacao-clay/sawdust-starch briquettes	Not reported	99.38/99.33	Glalah et al. (2024)
Industrial Charcoal Briquettes	Not reported	≈ 80.36	Kebede et al. (2022)
High-quality charcoal briquettes	>96.00	Not reported	Obi et al. (2022)
Starch-bonded charcoal briquette	98.40	Not reported	Yirijor et al. (2023)
Biochar briquettes (with various binders)	70.00-95.00	95.00-99.00	Ngene et al. (2024)

In the comparison of briquettes with and without glycerin, those without glycerin showed a lower shatter capability and lower durability, suggesting that they were friable and fragmented upon vertical drop from a height of 1.00 m onto concrete surface, reported as % shatter index and 1.50 m onto metal surface, reported as $\%D_r$. The low % shatter index and low $\%D_r$ might negatively affect solid fuels by making them more prone to breakage, reducing combustion efficiency, increasing dust generation, and raising environmental concerns due to particulate emissions (Kabas et al., 2022). The addition of glycerin significantly enhanced the mechanical integrity and shape stability of the briquettes, as reflected by the increased shatter index and durability (Figure 2). Moreover, the inclusion of glycerin as a binder in briquette production facilitates easier handling and storage under sunlight exposure without structural deterioration, which is attributable to glycerin's high boiling point and high viscosity compared to water (SDA, 1990). The high boiling point and viscosity could prevent its evaporation during storage and transport while maintaining its binding effectiveness, promoting strong adhesion between carbon particles and improving compactness. The high mechanical strength of briquettes might also be

attributed to the enhancement of thermal efficiency as well as extended shelf-life and usability (Winata et al., 2025).

3.1.2 Densification

Densification refers to the process of compressing biomass materials into a more compact form thereby increasing the bulk density and also reducing void spaces between particles. It significantly influenced the combustion behavior of the briquettes (Yang et al., 2025). The densification property directly correlated with the shatter capability and durability. Briquettes exhibiting high % shatter index and high $\%D_r$ also demonstrated high densification (Figures 2 and 3). The densification of studied briquette increased with increasing glycerin content from 0.00 to 60.00% by weight and increased with increasing carbonization temperature from 300°C to 500°C, as shown in Figure 3. The maximum densification was found to be at the highest glycerin content of 60.00% by weight and the highest carbonization temperature of 500°C. These results suggest that increasing the glycerin content to its highest level produced highly densified briquettes, similar to the densification achieved at the highest carbonization temperature. The densified briquettes not only affected the mechanical properties but also had a significant effect on combustion performance. The densified briquettes had a higher energy density, implying more energy stored per unit volume. Additionally, more complete combustion and more efficient heat transfer during combustion were supported by the compactness of the briquettes since the compactness of briquette might affect the airflow control and the combustion efficiency, which will be discussed later. According to Sarker et al. (2022), non-densified briquettes tend to have particles of varying sizes causing the different devolatilization rates of various gaseous products during the combustion process and unstable energy release that might be due to the incomplete combustion. In contrast to densified briquettes, which provide homogeneity in structure and moisture content, char burning and volatilization proceed simultaneously, promoting uniform heat release. Because of the uniform heat release and steady flame properties, a more prolonged and consistent generation of heat throughout the combustion process is enabled.

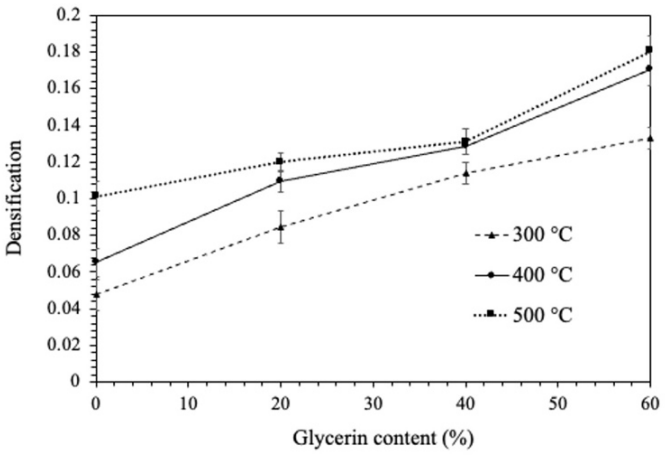


Figure 3. Densification of briquettes produced from sago palm residue at different carbonization temperatures and different glycerin contents

In this study, the densified briquettes were used as fuel to heat 20.00 mL of water from the liquid phase to the gas phase. The complete combustion of the studied briquettes was indicated by the absence of carbon powder at the end of combustion process. This was further supported by the grayer ash color and the high ash content (Figure 4), which gave the same result as Liang et al. (2024), who reported that a grayer ash color was associated with incomplete combustion. However, the low-density briquettes tended to have shorter burning durations because they allowed greater oxygen or air penetration and ignited more quickly, leading to faster burnout. Consequently, incomplete oxidation of volatile compounds, particularly light hydrocarbons such as methane (CH_4), ethane (C_2H_6), propane (C_3H_8) and butane (C_4H_{10}), occurred which was indicative of inefficient combustion (Jayasuriya et al., 2022). The briquettes produced in this study had densities ranging from 600 to 800 kg/m³, which were higher than those reported for rubberwood-based briquettes using fat sludge and molasses as binders—by approximately 8.11% to 33.33%, respectively (Menkoed et al., 2017). Interestingly, it is realized that the lower density of briquettes might have contributed to the greater consumption of fuel during the water boiling test; this will be discussed in more detail in the next section.

For an investigation of combustion completeness based on ash color at the end of the combustion process, ash color was found to be an important qualitative indicator of briquette combustion efficiency (Campbell et al., 2024). The test involved the boiling of 20.00 mL of water and comparison of the color of briquettes before and after combustion (Figure 4). In the present study, the ash produced from densified briquettes consistently exhibited a white to light gray color, suggesting a higher degree of combustion completeness. This indicated that most of the carbonaceous material was effectively oxidized to carbon dioxide (CO_2), leaving predominantly inorganic mineral residues such as potassium-containing compounds, calcium oxide (CaO), and silica (SiO_2). In contrast, the darker ash colors observed in non-densified briquettes, ranging from dark gray to brown or black, implied incomplete combustion and were commonly associated with residual unburned carbon, limited oxygen availability, and elevated fuel moisture content. These findings are consistent with the observations reported by Liang et al. (2024), which demonstrated that lighter gray ash is indicative of more complete combustion, whereas darker ash reflected the presence of unburned carbon.

3.1.3 Mass yield ratio (η_M)

The mass yield ratio is a fundamental parameter in the thermochemical conversion of sago palm residue into charcoal for briquette production. It represents the percentage of the original sago palm residue mass retained in the final solid product (the briquette) after carbonization process (equation 3) (Sarker et al., 2021).

$$\eta_M = \frac{M_t}{M_o} \times 100 \quad (3)$$

Where:

M_t is the weight of sago palm residue obtained after the carbonization process at different carbonization temperatures (g)

M_o is the weight of sago palm residue before the carbonization process (g)

The η_M is a crucial parameter because it directly influenced both the mechanical and thermal properties of briquettes (Sahupala & Kakerissa, 2022). In this study, the η_M

decreased as the carbonization temperature increased. The highest η_M was found to be at the lowest carbonization temperature of 300°C (Figure 4). At the lowest carbonization temperature, the devolatilization of organic volatile component in sago palm residue during the carbonization process was not complete (Owino et al., 2024), resulting in the partial release of organic volatile component from the sago palm residue. This meant that the final briquette product retained excess amount of organic volatile components, as tars and/or organic residues, and led to the final briquette product containing high volatile matter composition (%VM) (Table 2). A high volatile matter (VM) content significantly influenced the thermal characteristics of the final briquette product by enhancing ignitability, making it suitable for applications requiring rapid heating. Although a high VM content improved ignitability and promoted rapid heat release, it reduced combustion duration and thermal stability because of the associated decrease in fixed carbon content. From the investigation, it is possible to conclude that the lignin and cellulose components of the sago palm residue, that were providing for the % FC, were unable to be fully devolatilized into organic volatile components by breaking organic bonds, resulting in poor briquette combustion performance at low carbonization temperatures.

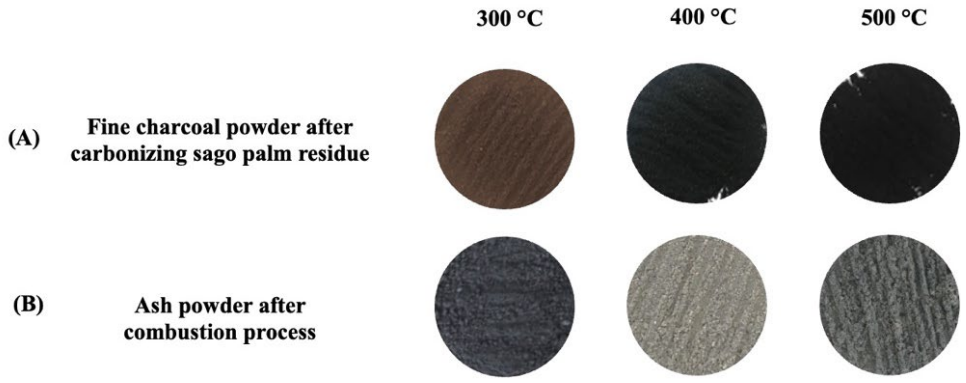


Figure 4. The color of (A) sago palm residue powder after carbonization process and (B) ash after burning for boiling 20.00 mL of water at different carbonization temperatures

The lignin, cellulose, and hemicellulose components of sago palm residue appear to have a specific temperature range for thermal decomposition under air-free condition (Wijitkosum, 2023). Based on thermogravimetric analysis (TGA) results for lignocellulosic biomass, the carbonization temperatures of 300°C, 400°C, and 500°C were chosen (Elkhalifa et al., 2022). These investigations revealed significant hemicellulose breakdown at roughly 200-300°C, significant cellulose breakdown between 300 and 400°C, and increasing char formation with higher fixed carbon content at temperatures over 400-500°C. The briquettes carbonized at 300°C showed a reddish-brown coloring, which is consistent with the different thermal breakdown ranges of lignin, cellulose, and hemicellulose under oxygen-free conditions (Wijitkosum, 2023) (Figure 1). On the other hand, as Figure 1 illustrates, briquettes produced at higher carbonization temperatures (400°C and 500°C) showed developing darker colors, ranging from dark brown to black. Increasing carbonization temperature from 300°C to 500°C progressively reduced mass yield (Figure 5), while porosity, mechanical strength, and fixed-carbon content increased (Figures 1 and 2 and Table 2). As illustrated in Figures 1 and 2, the briquettes carbonized at 300°C had poor mechanical strength but retained strong, acceptable physical integrity;

those carbonized at 400°C achieved a balance between strength and fuel quality; and those carbonized at 500°C reached the highest degree of carbonization but became more brittle due to extensive devolatilization and loss of natural binders. It might be implied that under the severe conditions (at the highest carbonization temperature of 500°C), the transformation of lignin component could be enhanced and led to the production of briquettes with high % FC (Table 2) (Bielecki & Zubkova, 2022). Biomass with a high lignin content might be provided with better briquette properties with high FC content.

Table 2 The proximate and ultimate composition of neat sago palm residue and briquettes which included and excluded 60.00% glycerin by weight at different carbonization temperatures

Carbonization Temperature (°C)	Glycerine Content (% weight)	Proximate Composition				Ultimate Composition					Heating Value (MJ/kg)
		%MC	%VM	%ASH	%FC	%C	%O	%H	%N	%S	
	Sago palm residue*	3.24	87.07	3.85	5.84	37.49	55.77	6.49	0.190	0.061	13.15
	Glycerin	11.47	85.17	3.36	N/A	46.39	38.48	9.60	< 0.01	< 0.01	21.87
300	0	4.66	76.24	5.86	13.24	47.79	32.85	4.14	0.566	0.104	16.06
300	60	11.46	83.82	3.48	1.24	41.92	40.92	6.65	0.210	< 0.01	17.13
400	0	2.17	37.14	10.37	50.32	58.48	40.77	3.89	0.704	0.156	18.63
400	60	3.18	62.14	8.44	26.24	56.39	23.93	5.05	0.390	< 0.01	22.15
500	0	2.27	29.80	12.97	54.96	54.52	23.35	2.71	0.621	0.129	18.94
500	60	3.98	79.91	11.04	5.07	53.89	23.39	4.72	0.390	0.07	21.00

Note: *Before carbonization

%MC	is moisture content.	%C	is carbon element content.
%VM	is volatile matter content.	%H	is hydrogen element content.
%ASH	is ash content.	%O	is oxygen element content.
%FC	is fixed carbon content.	%N	is nitrogen element content.
%S	is sulfur element content,		

3.2 Thermal properties of briquette

3.2.1 Energy yield ratio (η_E)

The energy yield ratio refers to the amount of energy retained in the briquette relative to the original biomass energy content (equation 4) (Sarker et al., 2021).

$$\eta_E = \frac{HV_t}{HV_o} \times \frac{M_t}{M_o} \times 100 \quad (4)$$

Where:

HV_t is heating value of charcoal after carbonization process (MJ/kg)
HV_o is heating value of initial sago palm residue (MJ/kg)

The η_E showed an opposite trend to the η_M, which increased with increasing carbonization temperatures from 300°C to 400°C, and then decreased when the carbonization temperature exceeded 400°C (Figure 5). The highest η_E was found at the carbonization temperature of 400°C. In agreement with the good mechanical characteristics of briquettes made from carbonized sago palm residue at 400°C (Figure 2), briquettes with high η_E indicated better energy retention after carbonization, greater heating performance, and improved fuel efficiency. The difference between the η_E and the η_M provided insight into the optimal condition for converting sago palm residue into charcoal through carbonization process, as quantified by the energy-mass co-benefit index (EMCI) (Mueanmas & Rakmak, 2024). The EMCI result had a similar trend to the η_E result. The highest EMCI was also found at the same carbonization temperature of 400°C (Figure 5), illustrating that under the carbonization process at 400°C, the system provided the optimal EMCI, which referred to an optimal condition for developing sago palm residue into charcoal. Since the η_M decreased with increasing temperature, the η_E and EMCI showed an adverse trend to the η_M. Despite a typical mass and organic volatile component loss taking place during the carbonization process, the high energy yield suggested that more than half of the biomass's initial energy was retained by the process. This helps to maximize the final fuel's energy potential. Under the optimum carbonization condition, an appropriate balance between the remaining fixed carbon (FC) and the loss of volatile matter (VM) was achieved, which contributed to enhanced overall thermal performance (Liu et al., 2022). Consequently, the briquettes attained a maximum heating value of 22.15 MJ/kg, which was 15.89% higher than that of commercial briquettes, attributable to their higher content of the combustible fixed carbon fraction (Pinho & Borges, 2025) (Table 3). Additionally, briquettes produced from carbonized sago palm residue had better thermal qualities, with a 31.74% greater heating value than carbonized sago bark due to the high FC content, as shown in Table 3 (Susanto et al., 2024).

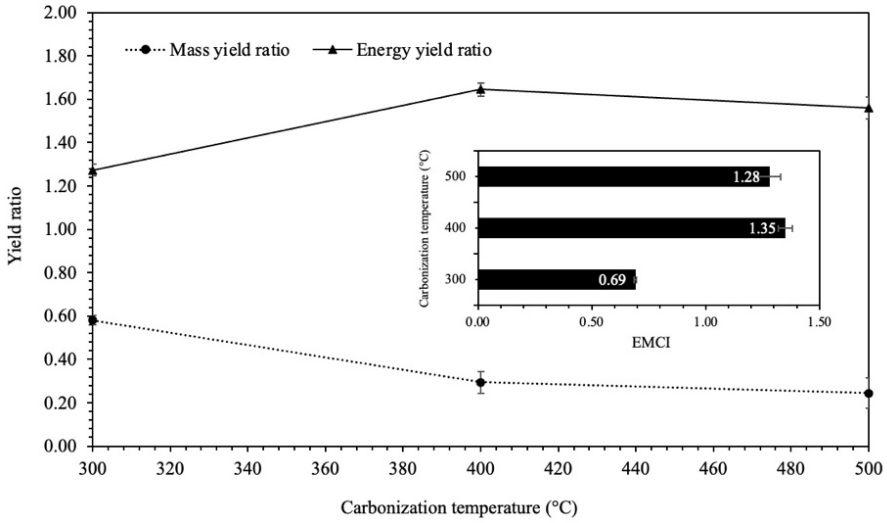


Figure 5. Mass yield ratio (η_M), energy yield ratio (η_E), and energy-mass co-benefit index (EMCI) of sago palm briquettes at different carbonization temperatures

3.2.2 Thermal efficiency of briquette

To determine the thermal efficiency of the produced briquettes, the samples containing the highest glycerin content (60.00% by weight) were chosen, as they exhibited the most desirable physical and thermal properties. A water boiling test was used to assess the thermal efficiency of the briquettes with and without a 60.00% glycerin addition. Thermal efficiency analysis was expressed as HV and energy density since HV is strongly related to the energy produced when the briquettes completely burn. Briquettes with higher HV might release more energy. Another essential characteristic of briquettes is their energy density, which reflects the amount of energy stored in each unit volume of fuel along with how many briquettes were used for boiling water (equation 5) (Portilho et al., 2020).

$$Energy\ density\ (Volumetric) = HV \times \rho_B \quad (5)$$

Where:
$Energy\ density\ (Volumetric)$ is in MJ/m³ unit
ρ_B is density of the briquette fuel (kg/m^3)
HV is heating value of the briquette (MJ/kg)

Under the same carbonization temperature of 400°C, briquettes with 60.00% added glycerin presented higher HV than those non-added. This is explained by the possibility that the incorporation of glycerin could result in lower ash composition (% ASH) (Table 2) (Wang et al., 2024). Ash is indicated as the non-combustible substances that are left after the briquette has completely burnt. The higher % ASH, the lower briquette HV is. At any given carbonization temperature, briquettes with added glycerin had a higher % VM than those without added glycerin, as indicated in Table 2. Glycerin is an organic substance that contains carbon (C), hydrogen (H), and oxygen (O), and can burn and generate energy easily. As a result, the briquettes produced more energy when glycerin was added. % VM represented the light hydrocarbon molecules as CH_4, C_2H_4, C_3H_8, C_4H_{10}, and others in briquettes that act as gaseous fuels and promoting in the ignition capability of briquette prior to the starting carbon combustion. Briquette with high % VM could be easier to ignite. Therefore, the presence of glycerin notably increased in % VM, resulting in an increase in HV of the briquette fuels.

At the same glycerin content of 60.00% by weight, the HV of the briquettes produced from carbonized sago palm residue at 400°C was higher than at 300°C and 500°C (Table 2). The higher HV of the 400°C carbonized sago palm residue briquettes was associated with the increase in combustible composition including % VM and % FC. Given the higher combustible composition, the extended burning duration after ignition allowed the briquettes to be more capable of retaining heat. This showed the greater energy density, which was reported to have increased by approximately 23.28% (e.g., the energy density of briquette produced from carbonized sago palm residue at 300°C was found to be 10,421 MJ/m³) (Lin et al., 2019). The use of glycerin as a binder also raised briquette energy density because it increased the fuel's mass without lowering its energy content. Furthermore, the high boiling point of glycerin might be difficult to evaporate during the combustion, which increases the amount of energy released. Consequently, adding glycerin greatly enhanced the briquette's thermal properties. This was in agreement with Asavatesanupap and Malee (2010), who reported that adding glycerol improved the HV of briquettes (Table 3). However, at carbonization temperatures beyond 400°C, the HV of the

added-glycerin briquette decreased, possibly because of greater proportion of non-combustible materials such as ash, which corresponded to low η_E.

To analyze the thermal efficiency of briquettes by the water boiling test, the produced briquettes were used as a fuel for heating 20.00 mL of water to its boiling point (100°C) from room temperature (30°C). Different quantities of briquettes were required based on their physical and thermal properties. The analysis found that briquettes produced from carbonized sago palm residue at 400°C required the least amount of fuel—8.48 g—which was comparable to those carbonized at 500°C. In contrast, briquettes produced from carbonized sago palm residue at 300°C needed significantly more fuel—12.83 g—to achieve the same result. This demonstrated that the higher heat retention capacity upon complete combustion led to a lower quantity of briquette needed to boil a specified water volume, which was consistent with the briquette fuel's higher energy density and higher HV. Regarding ignitability, briquettes with added glycerin revealed easier ignition, aligning with their high % VM. While the combustion duration, defined as the time from visible ignition until the complete burnout of carbon particles, was estimated by observing flame propagation and spark distribution across the briquette surface. The combustion duration of briquettes with high % VM or low % FC was approximately 11.13 min—about 2.65 times shorter than that of briquettes with higher % FC.

Table 3. The heating value (HV) of various types of briquettes

Briquette Type	Fixed Carbon (FC) (%)	Heating Value (HV) (MJ/kg)	Ref.
Sago palm residue with 60.00 wt% glycerin	26.24	22.15	This study
Commercial Pellets	20.82	18.63	Pinho and Borges (2025)
Sago bark	8.90	15.12	Susanto et al. (2024)
Rice husk	8.04	12.85	Ma et al. (2015)
Durian shell with 30.00 wt% waste glycerol	Not report	18.01	Asavatesanupap and Malee (2010)
Durian shell with 15.00 wt% waste glycerol	Not report	17.58	Asavatesanupap and Malee (2010)

3.3 Scalability of sago palm briquette production

Sago palm (*Metroxylon sagu*) is widely cultivated across Southeast Asia—especially in Indonesia, Malaysia, Papua New Guinea, and southern Thailand—where starch processing generates large volumes of lignocellulosic residues. These by-products are commonly treated as low-value waste. Previous studies indicated that sago palm plantations can produce 5-7 tons of dry biomass residue per hectare annually (Singhal et al., 2008; Moshawih et al., 2025), highlighting the abundance and year-round availability of this feedstock. Such consistent supply makes sago palm residue highly suitable for large-scale briquette production (Awg-Adeni et al., 2009; Fetriyuna et al., 2024).

Economically, the procurement cost is minimal because the residue originates from an agricultural waste stream. In addition, glycerin—the binder used in this study—is an inexpensive and widely available by-product of the biodiesel industry. The combination of low-cost biomass and readily accessible binder materials therefore enhances the feasibility and economic viability of scaling briquette production to industrial levels.

Recent assessments of agricultural residues report typical cost ranges of about 40-80 USD per dry ton, depending on region and logistics conditions (Kpalo et al., 2020). In contrast, crude glycerin is currently exhibiting market prices of the order of ≈ 300 USD per ton, reflecting its abundant supply and relatively low unit value (Moklis et al., 2023; Wang et al., 2024). According to those recent cost data, the raw material cost of sago palm residue is typically 40-80 USD per ton (Kpalo et al., 2020), whereas biodiesel-derived crude glycerin ranges around 300 USD per ton (Moklis et al., 2023; Wang et al., 2024). For a briquette formulation containing 60.00 wt% glycerin and 40.00 wt% carbonized sago palm residue, the estimated raw-material cost is approximately 200 USD per ton (ranging from 184-208 USD per ton depending on residue price), indicating that binder proportion has a major influence on production economics.

Energy consumption for briquette production was estimated using literature values for small- to medium-scale biomass densification systems, which typically consume 40-115 kWh per ton, depending on feedstock characteristics and plant configuration (Tufail et al., 2018). In this study, an average of 100 kWh per ton was adopted, assuming that sago palm residue is primarily sun-dried and requires minimal additional thermal input. Using Thailand's grid emission factor of 0.4999 $kgCO_2e/kWh$ (Thailand Greenhouse Gas Management Organization, 2022), the electricity-related emissions amount to approximately 49.99 $kgCO_2e$ per ton of briquettes, which aligns with previous LCA studies reporting carbon footprints of 40-110 $kgCO_2e$ per ton for wood pellets and briquettes (Soliño et al., 2008; Ilari et al., 2022). This was consistent with previous reviews showing that industrial briquette production relies on commercially available equipment (Kaliyan & Morey, 2009; Obi et al., 2022). Furthermore, modern biomass thermal-conversion reactors—including fixed-bed and rotary-kiln systems—are well established (Tumuluru et al., 2021; Slezak et al., 2023). The physical and thermal properties of sago palm residue have also been shown to be compatible with densification processes, supporting the feasibility of scale-up for industrial briquette production.

4. Conclusions

Briquette production from sago palm residue using the carbonization process at different carbonization temperatures and different glycerin content (functioned as a binding agent) was investigated. At both carbonization temperature of 400°C and glycerin content of 60.00% by weight, briquette exhibited the most favorable mechanical characteristics with the maximum of shatter capability and durability, corresponding to the highest bulk density. That was superior to biomass briquettes and commercial biochar. In addition, at the same carbonization temperature of 400°C, the system gave the best thermal characteristics of briquette in terms of the highest heating values and the highest energy density that was related to the lowest amount of fuel consumption for boiling 20.00 mL of water. Therefore, the carbonization temperature of 400°C was considerable to be an optimum condition for converting sago palm residue into charcoal. Moreover, the inclusion of glycerin as a binder also significantly balanced % VM with fixed carbon and densification. This was essential for optimizing the overall thermal performance of the produced briquettes and gave a

heating value that was 1.23 times higher than that of briquettes made from durian shell using waste glycerol as a binder.

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6. Authors' Contributions

Patcharee Intanoo: Writing – original draft, Writing – review & editing, Supervision, Resources, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.
Pitchayapon Klabklay: Writing – original draft, Project administration, Formal analysis, Data curation.

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7. Conflicts of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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