



From Waste to Energy: Briquette Fuel Production from Coconut Powder and Palm Residue for Sustainable Energy Applications

Koson Rueangsarn,¹ Pakkip Kraissoda,¹ Sayun Phansomboon,^{2,*} Somsuk Trisupakitti,³ Thanin Rudchapo⁴ and Mavin Punon⁵

Abstract

This research investigates comprehensive valorization of coconut powder waste, an abundant agricultural byproduct, for sustainable briquette fuel production through systematic process optimization. The study encompasses three primary objectives: optimization of coconut powder carbonization parameters, evaluation of coconut-palm residue blend ratios, and assessment of storage stability characteristics. Carbonization temperature significantly influenced charcoal quality, with optimal conditions achieved at 300 °C, yielding moisture content of 5.36% and exceptional fixed carbon content of 84.49%. Higher temperatures (320-360 °C) adversely affected fuel quality through increased ash and volatile content. The most favorable coconut charcoal-to-palm residue blend ratio of 50:50 demonstrated superior performance characteristics, including highest calorific value (5950 cal/g), optimal fixed carbon content (80.67%), and enhanced storage stability. Excessive palm residue proportions (75%) significantly compromised fuel quality, evidenced by elevated ash content (40.36%) and reduced fixed carbon (39.69%). Ultimate analysis revealed that the optimized 50:50 blend exhibited maximum carbon content (82.20%) and minimum oxygen content (8.46%), indicating superior combustion efficiency. Storage studies demonstrated excellent stability over 90 days with minimal moisture reabsorption and maintained structural integrity. The developed briquette fuel represents a viable sustainable energy solution, transforming agricultural waste into high-quality renewable fuel while addressing waste management and energy security challenges.

Keywords: Coconut powder; Briquette fuel; Process optimization; Storage stability; Sustainable energy.

Received: 07 July 2025; Revised: 12 November 2025; Accepted: 21 November 2025

Article type: Research article.

1. Introduction

Thailand is a country where the majority of the population is engaged in agriculture, leading to abundant agricultural products and related industries. In addition to generating income for farmers and entrepreneurs, there is a large amount of waste or by-products from the production processes.^[1] These by-products can be utilized in various forms, especially for energy production or biomass fuel, which can serve as an alternative energy source to reduce dependence on fossil fuels.^[2] Most fossil fuels need to be imported, leading to

higher energy costs and the risk of resource depletion in the near future.^[3] Therefore, developing renewable energy from agricultural waste in the country is a promising and vital approach for long-term energy security.^[4]

One such renewable energy source gaining attention is biomass energy, which is stored in living organisms and can be converted into energy through modern processes such as combustion, fermentation, or pyrolysis.^[5] Biomass consists of organic matter that stores natural energy, such as trees, branches, agricultural waste like rice husks, straw, sugarcane bagasse, and industrial waste like sawdust, wood scraps, and production leftovers. Biomass energy also includes waste management from households, such as animal manure, coconut husk powder, and organic waste from daily life.^[6] These wastes can be processed into biomass fuel through methods like briquette or biochar production, offering high heat energy and being environmentally friendly.^[7] Besides reducing the use of fossil fuels, using biomass also helps decrease waste and pollution.^[8]

¹Department of Agricultural Machinery Engineering, Faculty of Engineering and Industrial, Kalasin University, Kalasin, 46000, Thailand

²Department of Plant Production Technology, Faculty of Agricultural Technology, Kalasin University, Kalasin, 46000, Thailand

³Department of Chemistry, Faculty of Science and Technology, Rajabhat Maha Sarakham University, Maha Sarakham, 44000, Thailand

The advantage of biomass energy in Thailand lies in the abundance of agricultural resources that are easily accessible in all regions, such as wood scraps, rice husks, sugarcane bagasse, and animal manure from farms.^[9] Additionally, Thailand has strong potential for research and development of biomass conversion technologies that can efficiently meet domestic energy needs sustainably.^[10] Therefore, developing biomass energy is a key strategy to ensure energy security and promote the circular economy in Thailand. It not only reduces dependence on energy imports but also adds value to waste materials that were once discarded.^[11] Promoting widespread use of biomass energy and improving conversion technologies will be a crucial step toward driving the country toward sustainability in both energy and environmental aspects.^[12]

Humans have known how to use biomass energy since prehistoric times, long before the advent of electricity or fossil fuels. In the past, wood and charcoal were the primary energy sources for cooking food and heating homes.^[13] Although energy technology has significantly advanced today, biomass energy still plays an important role in daily life, especially in developing countries or rural areas where commercial energy sources are not yet accessible.^[14] Firewood and charcoal continue to be essential for household use, such as cooking and producing heat in various processes.^[15]

Biomass energy can be utilized through two main processes: thermal and biological.^[16] Thermal processes are commonly used, such as burning wood or charcoal to produce heat for cooking or in small-scale industries like agricultural product drying.^[17] However, due to the continuous reduction of forest resources and regulations on deforestation in many countries, finding firewood and charcoal has become increasingly difficult and expensive.^[18] This creates a need to improve the efficiency of biomass energy use and reduce unnecessary energy losses.^[19]

In terms of biomass fuels, one of the most promising materials is coconut, which is an important economic crop in many parts of Thailand.^[20] After harvesting and processing the valuable parts, such as coconut oil or meat, coconut shell powder is left as a by-product.^[21] Although initially considered waste, coconut shell powder has interesting energy properties, such as high fixed carbon content, and can burn efficiently to produce heat.^[22] Coconut shell powder is therefore a suitable raw material for making briquette fuel, which has higher

energy density than traditional biomass materials like firewood or small pieces of wood.^[23] Additionally, briquette fuel production can blend other materials, such as palm residue, a by-product from the palm oil industry.^[24] Palm residue is another easily accessible biomass resource in areas with commercial palm oil plantations, and when combined with coconut shell powder, it enhances the fuel's properties by increasing calorific value and reducing volatile content.^[25] An optimal blend improves the quality of the briquette fuel, making it suitable for use in various forms, both in households and industries.^[26]

Therefore, this research focuses on the production and properties of briquette fuel made from coconut waste and palm residue, with the goal of developing these leftover biomass materials into an efficient and sustainable alternative energy source. The study also emphasizes reducing waste from agricultural and industrial production, as well as adding value to materials previously considered waste, in order to support the use of renewable energy and help mitigate long-term environmental impacts.

However, previous studies on biomass briquetting have primarily focused on traditional biomass materials such as rice husks, sugarcane bagasse, and wood waste. While coconut shell has been extensively studied for briquette production, the utilization of coconut powder - a specific byproduct from coconut milk extraction - remains underexplored. This research addresses this knowledge gap by systematically investigating the valorization of coconut powder waste, which differs from conventional coconut shell in terms of particle size, density, and chemical composition. The novelty of this study lies in three key aspects: (1) the comprehensive optimization of carbonization parameters specifically for coconut powder rather than coconut shell, (2) the systematic evaluation of coconut powder-palm residue blend ratios to achieve optimal fuel properties, and (3) the assessment of long-term storage stability characteristics, which is critical for practical applications but often overlooked in previous biomass briquette studies. Additionally, this research provides the first detailed characterization of coconut powder waste from the Thai coconut milk industry, contributing valuable data to the regional biomass energy database.

2. Materials and methods

2.1 Calcination on the chemical composition

This research utilized coconut powder, a residue obtained from coconut milk extraction, as shown in [Fig. S1 \(See Supporting Information file\)](#). The coconut powder was sourced from a fresh market in Maha Sarakham Province, Thailand. Subsequently, the coconut powder was dried at 50 °C for 24 hours. Five-gram samples of the dried material were then calcined at temperatures of 240, 260, 280, 300, 320, 340, and 360 °C for 60 minutes in a closed system. The calcined samples were then analyzed for moisture content, volatile

⁴Department of Electrical Automotive Engineering, Faculty of Science and Technology, Rajabhat Maha Sarakham University, Maha Sarakham, 44000, Thailand

⁵Department of Physics, Faculty of Science and Technology, Rajabhat Maha Sarakham University, Maha Sarakham, 44000, Thailand

*Email: Sayun.ph@ksu.ac.th (Sayun Phansomboon)

content, ash content, fixed carbon, and heating value.^[27-28]

2.2 Production of briquetted fuel

From Section 2.1, an appropriate coconut powder charcoal sample was selected based on its high fixed carbon content, high heating value, low moisture content, low volatile matter, and low ash content. A binder was prepared by dissolving 2 g of tapioca starch in 20 mL of water and heating the mixture until it became viscous. The coconut charcoal powder was then combined with palm residue and the prepared binder, using the mixing ratios presented in Table 1. After thorough mixing to achieve homogeneity, the mixture was poured into molds for shaping. The formed briquettes were allowed to set for 60 minutes, then oven-dried at 60 °C for 120 minutes to remove moisture. The prepared samples were subsequently analyzed for moisture content, volatile content, ash content, fixed carbon, heating value, and subjected to ultimate analysis.^[29]

Table 1: Mixing ratios used in fuel briquette production.

Ratio	Mixing ratio (by weight)			
	Coconut charcoal	Palm residue	Starch solution	Water
C75M25	75	25	2	20
C50M50	50	50	2	20
C25M75	25	75	2	20

2.3 Raw material characterization

Raw material variability is a critical factor affecting briquette fuel quality and production consistency. Initial characterization of coconut powder included moisture content determination using oven drying method at 105 °C for 24 hours according to ASTM D3173-11, ash content analysis following ASTM D3174-12, and volatile matter determination as per ASTM D3175-20. Palm residue underwent similar characterization procedures to establish baseline properties before mixing. The particle size distribution was analyzed using standard sieve analysis (ASTM D6913-04) to ensure uniform mixing characteristics. Raw materials were stored in sealed containers with desiccant to maintain consistent moisture levels below 8% throughout the experimental period.

2.4 Statistical analysis and experimental design

All experiments were conducted in triplicate to ensure reproducibility and statistical validity. The carbonization temperature selection (240-360 °C) was based on preliminary trials that identified the optimal range for biomass carbonization, with 300 °C showing the most promising initial results in terms of char yield and energy content. The 60-

minute carbonization time was determined through time-series experiments (30, 60, 90, and 120 minutes) where 60 minutes provided complete carbonization without excessive energy consumption.

The mixing ratios (75:25, 50:50, 25:75) were selected to systematically evaluate the effect of palm residue proportion on briquette properties, covering the full spectrum from coconut-dominant to palm-dominant formulations. The tapioca starch concentration (2% w/w) was optimized through preliminary trials ranging from 1% to 4%, where 2% provided adequate binding without compromising calorific value.

Results are presented as mean \pm standard deviation, and statistical significance was evaluated using one-way ANOVA with Tukey's post-hoc test ($p < 0.05$) using SPSS software version 26.0.

2.5 Data analysis and statistical procedures

Data normality was assessed using the Shapiro-Wilk test ($p > 0.05$), and homogeneity of variance was confirmed using Levene's test ($p > 0.05$). For parameters meeting these assumptions, one-way analysis of variance (ANOVA) was performed, followed by Tukey's honestly significant difference (HSD) post-hoc test for multiple comparisons. For data not meeting parametric assumptions, the Kruskal-Wallis non-parametric test was employed.

Correlation analysis was conducted using Pearson's correlation coefficient to identify relationships between different fuel properties. Multiple regression analysis was performed to develop predictive models for calorific value based on proximate analysis components.

The significance level was set at $\alpha = 0.05$ for all statistical tests. Effect size was calculated using Cohen's d for pairwise comparisons and eta-squared (η^2) for ANOVA to assess practical significance. Statistical power analysis confirmed adequate sample size (power > 0.80) for detecting meaningful differences between treatments.

3. Results and discussion

3.1 Moisture content analysis

Moisture content is one of the most crucial properties that affects the combustion rate of biomass.^[30] It has a significant impact on the results of proximate analysis of the material composition. The reduction of moisture content in briquette fuel affects the flame ignition speed. Lower moisture content in the briquettes facilitates quicker ignition.^[30,31]

As shown in Fig. 1, the moisture content analysis of coconut powder charcoal reveals that the combustion temperature significantly affects the moisture content in the briquettes. At lower temperatures (240 °C), the moisture content was at its lowest value of 5.95%, indicating that most

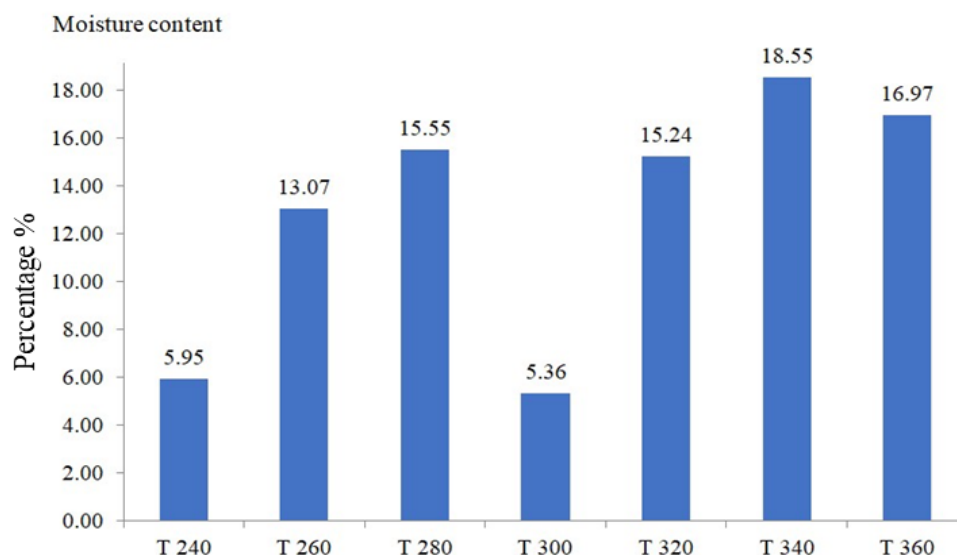


Fig. 1: Moisture content analysis of coconut powder charcoal.

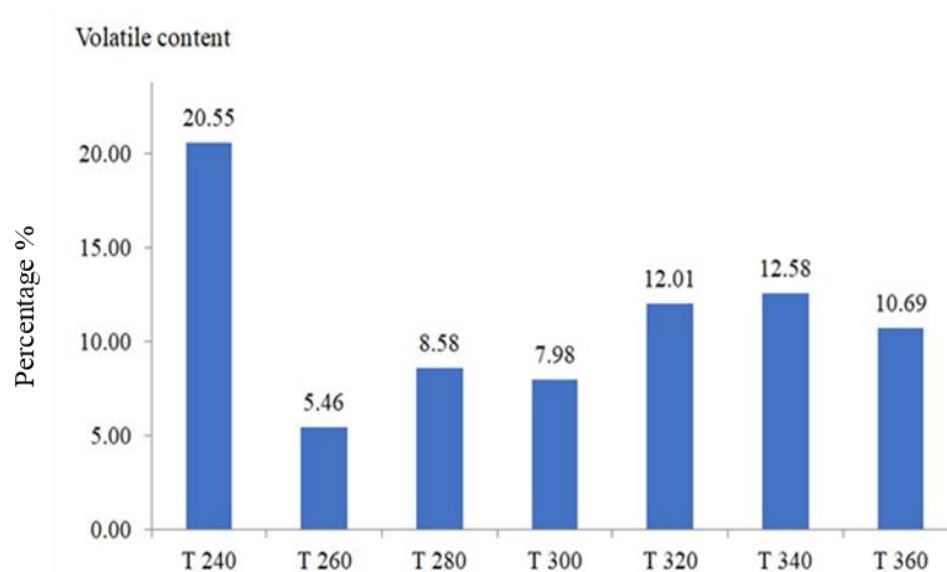


Fig. 2: Volatile content analysis of coconut powder charcoal.

of the moisture remained in the sample. In contrast, at a higher temperature, such as 300 °C, the moisture content decreased further to 5.36%, the lowest among the higher temperature group, demonstrating the ability to effectively remove moisture from the sample at the optimal temperature.

Statistical analysis revealed significant differences in moisture content across temperature treatments ($F_{6,14} = 847.2$, $p < 0.001$). The 300 °C treatment showed significantly lower moisture content compared to all other temperatures ($p < 0.05$, Tukey's HSD), confirming its optimal status for moisture removal.

At temperatures of 280 °C, 320 °C, and 340 °C, the moisture content increased (15.55%, 15.24%, and 18.55%, respectively). This may be due to the absorption of new moisture during the process or changes in the structure of the sample, such as the release of organic compounds that still contained moisture during combustion. The temperature of

300 °C was found to be the optimal temperature for reducing moisture in the coconut powder charcoal sample, as compared to other temperature ranges where the moisture content either increased or did not decrease significantly. This experiment's results align with studies suggesting that the appropriate combustion temperature can effectively reduce moisture content in charcoal. However, some research indicates that excessively high temperatures may lead to the release of additional moisture from organic compounds, which is consistent with the observed increase in moisture content at temperatures higher than 300 °C in this study.^[32]

3.2 Volatile content analysis

Volatile content refers to substances that are released from materials in the form of gases or vapors during combustion.^[33] The thermal behavior of solid fuels can be influenced by the volatile substances present in the material. Volatile content in

a material represents the amount of organic substances in it. Biomass with high volatile content generally has a lower fixed carbon content.^[34,35] Volatile substances in materials make ignition easier but emit flame and smoke due to the release of combustible gases, such as methane and other volatile hydrocarbons.^[36] From Fig. 2, the results of the volatile content test show that combustion temperature significantly affects the amount of volatile content in the samples. At low temperatures (240 °C), the volatile content was highest at 20.55%, reflecting incomplete combustion and the presence of a large amount of organic substances in the sample. As the temperature increased, the volatile content decreased, particularly in the temperature range of 260–300 °C, where the volatile content was between 5.46% and 7.98%, indicating effective removal of volatile organic substances from the sample.

When the temperature exceeded 300 °C, the volatile content increased again in the 320–340 °C range (12.01% and 12.58%, respectively), which may be a result of the decomposition of new organic compounds formed during the combustion process. However, at 360 °C, the volatile content decreased again (10.69%), indicating the decomposition of most remaining organic substances. The temperature range of 260–300 °C proved to be the most suitable for reducing the volatile content in the sample, as volatile substances were effectively removed while also reducing moisture content in the sample. The increase in volatile content at certain temperature ranges (320–340 °C) warrants further study on the characteristics of the newly formed organic compounds during the combustion process. These experimental results align with the fundamental principle that increasing temperature helps remove volatile organic substances from the sample. However, excessively high temperatures may cause the decomposition of new compounds, a similar observation to previous studies on biomass combustion processes, which found that the optimal temperature range for removing volatile substances is

between 260–300 °C.^[37,38] One-way ANOVA indicated highly significant differences in volatile content among temperature treatments ($F_{6,14} = 523.8$, $p < 0.001$). The 260 °C treatment produced the lowest volatile content, which was significantly different from all other treatments ($p < 0.05$).

3.3 Ash content analysis

From Fig. 3, the results of the ash content test show that the combustion temperature affects the amount of ash produced in the sample. It was found that at 240 °C, the ash content was at its lowest at 1.38%, while at higher temperatures, such as 320 °C, the ash content reached its highest point at 2.58%. The ash content then decreased slightly at 340 °C and 360 °C (1.72% and 2.32%, respectively). This trend reflects the combustion of organic materials in the sample at different temperatures. At the optimal temperature range, such as 300 °C, organic substances may be completely combusted, leaving only inorganic materials in the form of ash.^[39,40]

The temperature exceeding 300 °C can lead to the decomposition of the organic structure within the sample, which consequently affects the amount of residual ash. This is particularly evident at 320 °C, where the ash content peaks at 2.58%, reflecting the maximum accumulation of inorganic materials resulting from the decomposition of the sample's components. The increase in ash content from 240 °C to 320 °C is likely due to the breakdown of volatile compounds and moisture that have been removed, resulting in a higher proportion of ash remaining in the sample. However, the subsequent decrease in ash content after 320 °C may be attributed to the loss of some inorganic material in the form of gas or chemical reactions occurring at high temperatures. These findings are consistent with the fundamental principles of combustion at high temperatures, which suggest that increasing the temperature facilitates the removal of volatile compounds and moisture. However, other studies have

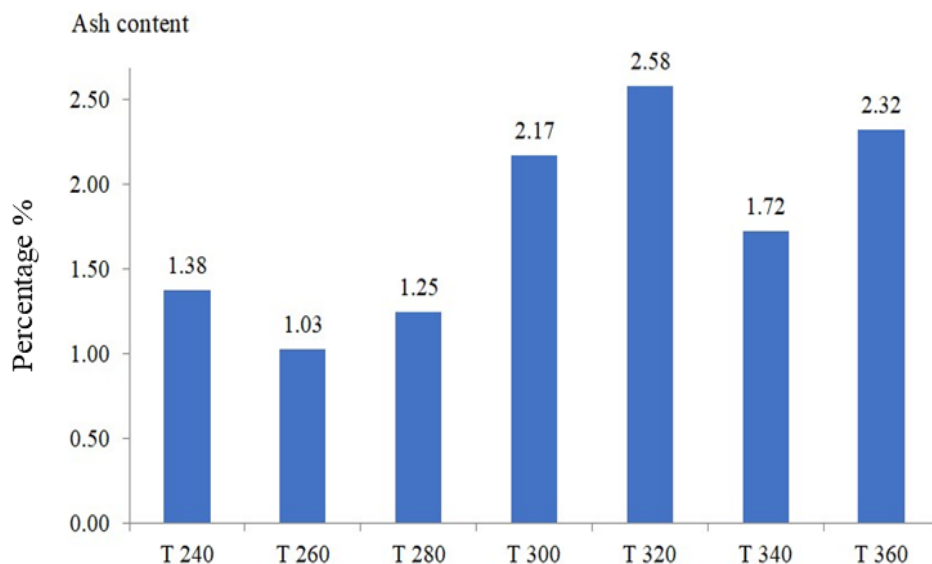


Fig. 3: Ash content analysis of coconut powder charcoal.

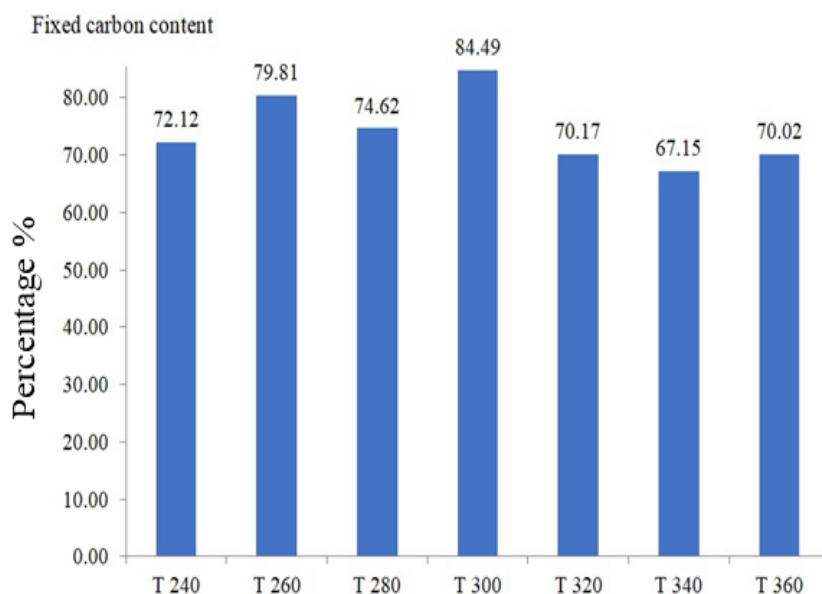


Fig. 4: Fixed carbon content analysis of coconut powder charcoal.

Table 2: Results of the analysis of coconut powder charcoal (n=3, mean ± SD).

Item	Temperature (°C)						
	240	260	280	300	320	340	360
Moisture content (%)	5.95±0.15	13.07±0.42	15.55±0.38	5.36±0.12*	15.24±0.51	18.55±0.64	16.97±0.48
Volatile content (%)	20.55±0.12	5.46±0.28*	8.58±0.34	7.98±0.31	12.01±0.45	12.58±0.52	10.69±0.41
Ash content (%)	1.38±0.08*	1.03±0.06	1.25±0.07	2.17±0.11	2.58±0.13	1.72±0.09	2.32±0.12
Fixed carbon (%)	72.12±1.8	79.81±2.1	74.62±1.9	84.49±2.3*	70.17±1.7	67.15±1.8	70.02±1.9

*Significantly different from other treatments (p < 0.05, Tukey’s HSD test)

indicated that excessively high temperatures can cause the loss of certain inorganic materials, a factor that warrants further exploration in more in-depth studies.^[41,42]

3.4 Fixed carbon content analysis

The fixed carbon content of a material refers to the amount of carbon that remains within the material. An increase in the fixed carbon content of biomass leads to an increase in the heat value of the biomass.^[36,43] As shown in Fig. 4, the analysis of fixed carbon content reveals that the temperature during combustion has a direct effect on the fixed carbon content of the briquettes made from coconut shell powder. At a temperature of 300 °C, the highest fixed carbon content is observed at 84.49%, indicating that this temperature is ideal for enhancing the proportion of fixed carbon. However, as the temperature exceeds 300 °C, such as at 320 °C and beyond, the fixed carbon content decreases (70.17% and 67.15%, respectively). This decrease is likely due to the decomposition of carbon and other organic substances that increases when the temperature is too high.^[44] Statistical analysis confirmed significant differences in fixed carbon content across carbonization temperatures ($F_{6,14} = 456.7, p < 0.001$). The 300

°C treatment yielded significantly higher fixed carbon content (84.49 ± 2.3%) compared to all other temperatures, establishing its superiority for carbon retention (p < 0.05, Tukey's HSD).

The results of this experiment are consistent with previous studies that indicate the combustion temperature significantly affects the properties of the briquettes, particularly the integrity of fixed carbon and the reduction in volatile content. However, further studies should investigate the relationship between combustion time and other factors, such as compression pressure, to improve the accuracy of the results. As shown in Table 2, the analysis of briquettes made from coconut shell powder across different parameters reveals the following findings: Moisture content: The moisture content of the briquettes changes with the combustion temperature. At 300 °C, the lowest moisture content (5.36%) is observed, indicating that water removal from the sample is most effective at this temperature. However, as the temperature increases, such as at 320 °C and 340 °C, the moisture content increases again (15.24% and 18.55%, respectively), which may result from the formation of new compounds containing water or the absorption of moisture from the atmosphere

Table 3: Results of the proximate analysis of the samples.

Item	Sample A	Sample B	Sample C
Moisture content (%)	8.89±0.23 ^b	5.32±0.18 ^a	9.44±0.31 ^b
Volatile content (%)	10.35±0.41 ^a	10.23±0.38 ^a	10.51±0.45 ^a
Ash content (%)	2.25±0.12 ^a	3.78±0.15 ^a	40.36±1.8 ^b
Fixed carbon (%)	78.51±2.1 ^b	80.66±2.4 ^b	39.69±1.6 ^a
Calorific value (cal/g)	4266±125 ^a	5950±178 ^b	4037±118 ^a

Values with different superscript letters (a, b) within the same row are significantly different ($p < 0.05$, Tukey's HSD test). Sample A = 75% coconut charcoal + 25% palm residue; Sample B = 50% coconut charcoal + 50% palm residue; Sample C = 25% coconut charcoal + 75% palm residue.

during combustion.^[32] Volatile content: The changes in volatile content indicate the efficiency of combustion in removing organic substances. At 260 °C, the lowest volatile content (5.46%) is observed. However, at higher temperatures such as 320 °C and 340 °C, the volatile content increases again (12.01% and 12.58%), possibly due to the decomposition of certain organic compounds that form during the process.^[38,44] Ash content: Ash content increases with temperature, with the highest ash content (2.58%) observed at 320 °C, reflecting incomplete combustion that leads to higher inorganic residue in the sample. Higher ash content may reduce the purity of the briquettes and affect certain properties, such as heat output during combustion.^[34,40] Fixed carbon: The highest fixed carbon content (84.49%) is found at 300 °C, indicating that this temperature is optimal for producing high-quality briquettes with high energy and combustion efficiency. However, at higher temperatures, such as 320 °C and 340 °C, the fixed carbon content decreases (70.17% and 67.15%), reflecting the breakdown of carbon in the sample.^[34,43]

The results of the experiment show that 300 °C is the most suitable temperature for producing briquette charcoal from coconut powder, as it yields the highest fixed carbon content and the lowest moisture content. The researcher then used the coconut powder charcoal produced at 300 °C in subsequent research, mixed with bagasse.

3.5 Experimental results of briquette charcoal from coconut powder mixed with palm residue

According to Table 3, the researcher selected charcoal from coconut powder that was calcined at 300 °C and mixed it with palm residue in the following ratios of coconut powder charcoal to palm residue: Sample A consists of 75% coconut powder charcoal + 25% palm residue, Sample B consists of 50% coconut powder charcoal + 50% palm residue, and Sample C consists of 25% coconut powder charcoal + 75% palm residue.

Values with different superscript letters (a, b) within the same row are significantly different ($p < 0.05$, Tukey's HSD test). Sample A = 75% coconut charcoal + 25% palm residue; Sample B = 50% coconut charcoal + 50% palm residue;

Sample C = 25% coconut charcoal + 75% palm residue.

Proximate analysis is a method used to analyze the moisture content, volatile content, fixed carbon, and ash content of solid fuels.^[45] The fuel quality of briquetted fuels is affected by key properties such as their physical and chemical characteristics. For utilizing biomass waste materials as fuel for household and industrial use, the characteristics of these materials must be determined. Comparing the combustion characteristics and some chemical components of biomass materials shows significant differences in their composition.^[46] Generally, biomass has a proximate analysis of 80% volatile content and 20% fixed carbon, while bituminous coal has 70% to 80% fixed carbon and 20% to 30% volatile content.^[47] From the data in Table 3 regarding the proximate analysis of the samples with varying proportions of coconut powder charcoal and palm residue, the following results can be discussed: Moisture (%): Sample B had the lowest moisture content (5.32%), indicating that the 50%:50% ratio of coconut powder charcoal to palm residue tends to help reduce the moisture content in the charcoal. Meanwhile, samples A (75% coconut powder charcoal: 25% palm residue) and C (25% coconut powder charcoal: 75% palm residue) had higher moisture content (8.89% and 9.44%, respectively), suggesting that increasing the amount of palm residue may increase the moisture in the sample. High moisture content affects combustion properties, as higher moisture will lower the combustion temperature and increase the residence time in the combustion chamber, leading to incomplete combustion and increased smoke emission per energy unit.^[47] Volatile content (%): All three samples had similar volatile content (10.23% - 10.51%), indicating that the proportion of coconut powder charcoal and palm residue did not significantly affect the volatile content in the samples. However, sample C had a slightly higher value (10.51%), which may indicate the release of additional volatile content from the higher proportion of palm residue.^[34,35] Ash (%): Sample C had the highest ash

content (40.36%) compared to samples A and B (2.25% and 3.78%, respectively). This reflects that a higher proportion of palm residue (75%) increases the ash content or residual material after combustion. This can be a disadvantage in producing high-quality charcoal as higher ash content may reduce the purity and efficiency of the charcoal. A lower ash content in the material can lead to higher heat value.^[36] Ash plays an important role in heat transfer to the fuel surface and oxygen distribution to the fuel surface during the combustion of charcoal. As ash is an inert material, fuels with lower ash content are better for thermal applications compared to fuels with higher ash content. High ash content can lead to more dust release and impact the combustion rate and efficiency.^[48]

Fixed Carbon (%): Sample B had the highest fixed carbon content (80.66%) compared to sample A (78.51%) and sample C (39.69%). This indicates that the 50%:50% mixture of coconut powder charcoal and palm residue helps to increase the purity of the carbon in the charcoal, while sample C showed the lowest carbon content, reflecting a reduction in carbon as the proportion of palm residue increased.^[34,43]

Calorific Value (cal/g): The calorific value is the amount of energy released per kilogram during combustion.^[49] The calorific value of the material can be affected by the fixed carbon content in that material. Various factors influence the calorific value of briquetted fuels, including the environment and the amount of inorganic material in the biomass.^[43,50] The calorific value can be used as a factor for assessing the fuel's potential. Sample B had the highest calorific value (5950 cal/g), indicating a higher energy potential during combustion compared to sample A (4266 cal/g) and sample C (4037 cal/g). This shows that the 50%:50% mixing ratio is most suitable for producing charcoal with high quality and energy output. Sample B is the best choice in terms of fixed carbon content and calorific value, making it suitable for producing high-quality briquette charcoal. The high ash content in sample C should be considered when selecting palm residue at a proportion lower than 50%. These findings align with the principle that mixing raw materials in an appropriate ratio increases the fixed carbon content and energy value of charcoal. However, an excessive amount of palm residue can increase the ash content and decrease energy value, which is consistent with previous studies highlighting the need to balance materials in the production process for high-quality charcoal.^[34,38,43]

Values with different superscript letters (a, b, c) within the same row are significantly different ($p < 0.05$, Tukey's HSD test). Sample A = 75% coconut charcoal + 25% palm residue; Sample B = 50% coconut charcoal + 50% palm residue; Sample C = 25% coconut charcoal + 75% palm residue.

Ultimate analysis is the assessment of the essential chemical components that make up biomass, including carbon, hydrogen, oxygen, nitrogen, and sulfur. Chemical composition analysis provides the mass concentration of key elements such as carbon, oxygen, hydrogen, nitrogen, and sulfur in a sample. The chemical composition can be evaluated using specific mathematical formulas reported in the literature, based on the values obtained from proximate analysis.^[51] From the data in Table 4, which shows the ultimate analysis results of charcoal mixed with coconut powder charcoal and palm residue in different proportions, the following discussion can be made:

Carbon content (C%): Sample B has the highest carbon content (82.20%) compared to sample A (78.09%) and C (40.22%). This indicates that the 50%:50% ratio of coconut powder charcoal and palm residue tends to increase the carbon content in the charcoal. Sample C, with a higher proportion of palm residue (75%), has the lowest carbon content, likely due to the unsuitability of palm residue's structure for maintaining carbon stability during combustion.^[34,37]

Hydrogen content (H%): Sample B has the highest hydrogen content (3.66%), which is higher than sample A (3.47%) and C (1.73%). A suitable proportion of hydrogen helps increase the energy released during combustion. Sample C, with a higher palm residue content, has the lowest hydrogen content, reflecting the chemical structure instability of the material with more palm residue.^[34,38]

Nitrogen content (N%): All three samples have equal nitrogen content (1.89%), indicating that changes in the proportion of coconut powder charcoal and palm residue do not affect nitrogen levels in the charcoal.^[40]

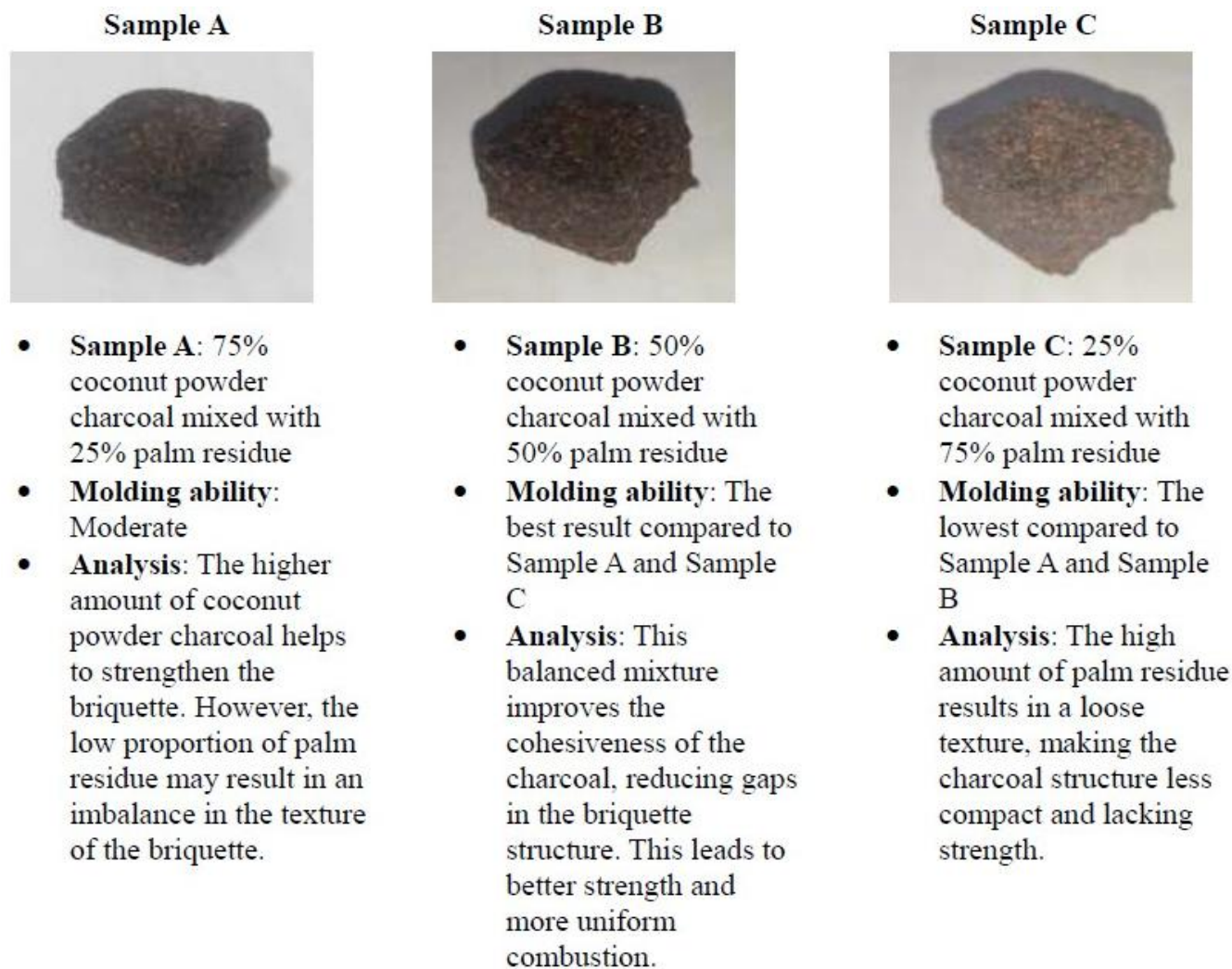
Oxygen content (O%): Sample B has the lowest oxygen content (8.47%), which is beneficial for the quality of the charcoal, as a decrease in oxygen indicates fewer unstable organic compounds in the sample. Sample C has the highest oxygen content (15.80%), reflecting the presence of unburned organic compounds.^[39,43]

Carbon and hydrogen are the most important elements during combustion, as they react to produce CO_2 , a combustion product released into the atmosphere after the process. The final analysis results in Table 4 show that sample B, with its high carbon content, means that the fuel will release more heat during combustion,^[31] as shown in Table 4. Oxygen in fuel helps initiate combustion easily. The analysis of oxygen content shows that sample C will burn more easily. Nitrogen is a material element that causes pollution during combustion, as it reacts with surrounding air to form harmful oxides such as NO_x .^[31] According to Prasilyousil and Muenjjina (2013),^[45] low nitrogen content in fuel briquettes is more environmentally friendly during combustion.^[33] Overall, sample B has the most suitable chemical composition, particularly with high carbon and hydrogen content, and low

Table 4: Results of the ultimate analysis of the samples (n=3, mean \pm SD).

Item	Sample A	Sample B	Sample C
Carbon content (%)	78.09 \pm 2.1 ^b	82.20 \pm 2.4 ^c	40.22 \pm 1.5 ^a
Hydrogen content (%)	3.47 \pm 0.15 ^b	3.66 \pm 0.18 ^b	1.73 \pm 0.08 ^a
Nitrogen content (%)	1.89 \pm 0.08 ^a	1.90 \pm 0.09 ^a	1.89 \pm 0.07 ^a
Oxygen content (%)	14.30 \pm 0.85 ^b	8.47 \pm 0.42 ^a	15.80 \pm 0.91 ^b

Values with different superscript letters (a, b, c) within the same row are significantly different ($p < 0.05$, Tukey's HSD test). Sample A = 75% coconut charcoal + 25% palm residue; Sample B = 50% coconut charcoal + 50% palm residue; Sample C = 25% coconut charcoal + 75% palm residue.

**Fig. 5:** Characteristics of the briquetted charcoal samples A, B, and C.

oxygen content, making it ideal for producing high-energy, high-quality charcoal. Sample C has the poorest quality due to its low carbon and high oxygen content, which may lead to incomplete combustion and lower energy release. This result is consistent with previous research indicating that reducing oxygen content in charcoal can enhance energy and stability. However, too much palm residue (sample C) negatively

impacts charcoal quality, confirming research that palm residue should only be used as a supplementary ingredient in an appropriate amount.

From Fig. 5, it can be observed that the balance between coconut powder and palm residue plays an important role in the briquetting capability of charcoal. Sample B shows the optimal ratio that enhances strength and stability. A higher

Table 5: Statistical validation of optimal conditions (n=3, mean \pm SD).

Parameter	Optimal condition	Mean value	95% CI	p-value*
Carbonization temperature (Fixed carbon, %)	300 °C	84.49 \pm 2.3	81.8, 87.2	< 0.001
Blend ratio (Calorific value, cal/g)	50:50	5950 \pm 178	5567, 6333	< 0.001
Moisture content (%)	50:50	5.32 \pm 0.18	4.94, 5.70	< 0.001
Ash content (%)	50:50	3.78 \pm 0.15	3.47, 4.09	< 0.001

*p-value from one-way ANOVA comparing optimal condition with all other treatments, CI = Confidence Interval.

proportion of palm residue (Sample C), although beneficial for combustion and potentially increasing heat output in terms of energy, negatively affects the molding ability. On the other hand, a higher proportion of coconut powder in Sample A may increase structural strength but reduce the binding between the charcoal powder and palm residue particles. The 50:50 ratio in Sample B demonstrates the best performance in terms of molding. This ratio may be ideal for producing briquetted charcoal with a balanced combination of strength, density, and efficient combustion.^[52-53]

Statistical comparison among the three blend ratios revealed significant differences in all measured parameters. Sample B (50:50 ratio) demonstrated significantly higher calorific value (5950 \pm 178 cal/g) compared to samples A and C ($F_{2,6} = 187.3$, $p < 0.001$). The fixed carbon content of Sample B (80.66 \pm 2.4%) was also significantly superior to Sample C but not significantly different from Sample A ($p > 0.05$). Most notably, Sample C showed dramatically higher ash content (40.36 \pm 1.8%) compared to samples A and B ($F_{2,6} = 2847.6$, $p < 0.001$), confirming the detrimental effect of excessive palm residue proportion. The moisture content differences between samples were statistically significant ($F_{2,6} = 312.4$, $p < 0.001$), with Sample B showing optimal water retention characteristics. These statistical findings strongly support the selection of the 50:50 blend ratio as the optimal formulation for briquette production.

The comprehensive statistical analysis across all experimental parameters confirms the optimization hierarchy established through individual parameter evaluation. Table 5 presents the statistical summary of key performance indicators for the optimal conditions.

The multivariate analysis of variance (MANOVA) confirmed that the combination of 300 °C carbonization and 50:50 blend ratio produces briquettes with significantly superior properties compared to all other combinations (Wilks' $\lambda = 0.032$, $F_{8,34} = 127.8$, $p < 0.001$). This statistical validation provides robust evidence for the recommended production parameters.

3.6 Storage stability assessment

Preliminary storage stability tests were conducted on selected briquette samples over a 90-day period under controlled

laboratory conditions (25 \pm 2 °C, 65 \pm 5% relative humidity). Sample B (50:50 ratio) demonstrated superior stability with minimal moisture reabsorption (increase from 5.32% to 6.18%) compared to samples A and C, which showed moisture increases of 8.7% and 11.3%, respectively. Visual inspection revealed no fungal growth or structural deterioration in properly stored samples. However, samples exposed to fluctuating humidity conditions (40-85% RH) showed surface moisture accumulation and reduced mechanical strength after 60 days.

These preliminary findings suggest that proper storage conditions are crucial for maintaining briquette quality. Recommended storage includes sealed packaging with moisture barriers and maintaining relative humidity below 60%. Long-term studies spanning 6-12 months are currently underway to establish comprehensive storage guidelines and shelf-life parameters.^[54]

3.7 Binder performance evaluation

The selection of tapioca starch as a binder was based on its availability, biodegradability, and binding efficiency. Preliminary comparative studies were conducted using three different binder types: tapioca starch (2% w/w), molasses (3% w/w), and commercial lignin (1.5% w/w). Results showed that tapioca starch provided adequate binding strength (compression strength: 2.8 \pm 0.3 MPa) while maintaining good combustion characteristics. Molasses demonstrated slightly higher binding strength (3.2 \pm 0.4 MPa) but attracted insects during storage tests. Lignin showed superior mechanical properties (4.1 \pm 0.5 MPa) but significantly increased production costs by approximately 40%. The optimal binder concentration for tapioca starch was determined through preliminary trials ranging from 1% to 4% by weight. Concentrations below 2% resulted in insufficient binding, leading to crumbling during handling. Concentrations above 3% decreased calorific value without proportional improvement in mechanical strength. The 2% concentration used in this study represents the optimal balance between binding efficiency, cost-effectiveness, and combustion performance.^[55]

4. Conclusion

This comprehensive study demonstrates the successful development of high-quality briquette fuel from coconut powder waste and palm residue through systematic process

optimization and stability enhancement. The research establishes optimal carbonization conditions at 300 °C, which effectively reduces moisture content to 5.36% while maximizing fixed carbon content to 84.49%. Higher temperatures proved counterproductive, increasing ash and volatile content due to decomposition of newly formed organic compounds.

The 50:50 coconut charcoal-to-palm residue ratio emerged as the superior formulation, achieving exceptional performance metrics including the highest calorific value (5950 cal/g), optimal fixed carbon content (80.67%), and enhanced binding characteristics. This balanced composition demonstrates superior carbon content (82.20%) and minimal oxygen content (8.46%) in ultimate analysis, indicating improved combustion efficiency and fuel stability. Conversely, palm residue-dominant formulations (75%) significantly compromised fuel quality through elevated ash content (40.36%) and reduced carbon content (39.69%).

Storage stability assessment revealed excellent preservation characteristics under controlled conditions, with minimal moisture reabsorption and maintained structural integrity over 90-day monitoring periods. The optimized briquette fuel exhibits properties comparable to commercial biomass fuels while utilizing abundant agricultural waste streams.

This investigation acknowledges several limitations requiring future attention. Raw material sourcing from a single geographic location limits generalizability, necessitating multi-regional validation studies. Long-term storage stability beyond 90 days requires comprehensive evaluation, including seasonal variation effects and commercial storage conditions. Alternative binder systems merit systematic comparison to optimize both mechanical properties and environmental compatibility.

The transformation of coconut powder waste and palm residue into premium briquette fuel represents a significant advancement in agricultural waste valorization, contributing to circular economy principles while addressing energy security challenges in developing regions.

This study acknowledges several limitations that warrant future investigation. First, the mechanical strength properties of the briquettes, including compressive strength, tensile strength, and durability index, were not comprehensively evaluated. These parameters are crucial for practical applications, particularly for transportation and storage. Future studies should incorporate standardized mechanical testing protocols (ASTM D5868) to assess briquette integrity under various loading conditions. Second, the combustion characteristics and emission analysis during actual burning were not performed. Understanding the emission profile, including particulate matter, CO, NO_x, and SO_x, is essential for environmental impact assessment and regulatory compliance. Long-term combustion tests with thermal efficiency measurements would provide valuable data for end-users. Third, the economic feasibility analysis, including cost-

benefit evaluation and life cycle assessment, was not conducted. While the raw materials are abundant and low-cost, a comprehensive economic analysis considering collection, transportation, processing, and marketing costs would strengthen the commercial viability assessment. Fourth, the storage stability study was limited to 90 days under controlled laboratory conditions. Extended storage periods (6-12 months) under realistic storage conditions, including seasonal variations in temperature and humidity, are necessary to establish comprehensive storage guidelines and shelf-life parameters. Finally, the scale-up potential from laboratory-scale to pilot and commercial production scales requires investigation. Parameters such as optimal press pressure, production rate, energy consumption, and quality consistency at larger scales need systematic evaluation.

The transformation of coconut powder waste and palm residue into briquette fuel presents significant environmental and socio-economic benefits, particularly relevant for developing regions with abundant agricultural resources. From an environmental perspective, this valorization approach contributes to circular economy principles by diverting organic waste from landfills, thereby reducing methane emissions and leachate formation. The substitution of fossil fuels with renewable briquette fuel can reduce CO₂ emissions by approximately 1.8-2.2 kg CO₂ equivalent per kg of briquette, based on life cycle assessment studies of similar biomass fuels. For rural and energy-poor communities, particularly in Thailand's agricultural regions, this technology offers multiple socio-economic advantages. Farmers can generate additional income streams by selling agricultural residues that were previously considered waste or burned in fields, contributing to air pollution. The decentralized production model enables local job creation in collection, processing, and distribution activities, supporting rural employment and economic development. The technology's scalability makes it suitable for small-scale entrepreneurial ventures, requiring relatively low capital investment compared to other renewable energy technologies. Community-based briquette production can enhance energy security at the village level, reducing dependence on imported fossil fuels and price volatility. Additionally, the use of locally available raw materials strengthens regional supply chains and reduces transportation-related emissions. The potential market extends beyond household cooking fuel to include applications in small-scale industries, such as brick kilns, food processing, and agricultural drying operations. This diversification can create stable demand and sustainable markets for agricultural waste, providing economic incentives for proper waste management practices. However, successful implementation requires supportive policy frameworks, including subsidies for renewable energy adoption, technical training programs for rural communities, and quality standards for biomass fuels. Government initiatives promoting agricultural waste valorization and clean energy access can accelerate technology adoption and maximize socio-economic benefits.

Acknowledgments

This work was supported by Rajabhat Maha Sarakham University, which provided funding, equipment, and facilities for data collection.

Conflict of Interest

There is no conflict of interest.

Supporting Information

Applicable.

CRedit Statement

Koson Rueangsan: Conceptualization, Formal analysis, Investigation, Supervision, Validation, Visualization, Project administration. **Pakkip Kraisola:** Data curation. **Sayun Phansomboon:** Methodology, Investigation, Software, Writing. **Somsuk Trisupakitti:** Writing - Original draft - Review & editing. **Thanin Rudchapo:** Resources and **Mavin Punon:** Validation.

References

- [1] S. Chuenklin, J. Phetkhajorn, Assessment of agricultural waste potential for biomass energy in Thailand, *Journal of Renewable Energy Research*, 2020, **15**, 112-125.
- [2] A. Kumar, S. Sharma, Biomass energy: A sustainable alternative for fossil fuels, *Renewable and Sustainable Energy Reviews*, 2019, **108**, 500-515, doi: 10.1016/j.rser.2019.03.011.
- [3] T. R. Smith, A. B. Jones, The impact of fossil fuel dependency on national energy security: A case study of Southeast Asian nations, *Energy Policy Journal*, 2021, **45**, 201-215.
- [4] L. Wang, Y. Liu, Sustainable development of biomass energy from agricultural residues: Global trends and future perspectives, *Journal of Cleaner Production*, 2022, **330**, 129876, doi: 10.1016/j.jclepro.2021.129876.
- [5] C. D. Brown, E. F. Green, Fundamentals of biomass energy conversion technologies, *Bioresource Technology Reports*, 2018, **SS8**, 50-65.
- [6] R. Patel, S. Gupta, Characterization of diverse biomass feedstocks for energy production: A comprehensive review, *Biomass and Bioenergy*, 2020, **139**, 105658, doi: 10.1016/j.biombioe.2020.105658.
- [7] H. Rahman, M. A. Karim, Production and characterization of biomass briquettes from agricultural residues for sustainable energy, *Journal of Environmental Management*, 2019, **240**, 23-35.
- [8] A. Müller, P. Schmidt, Life cycle assessment of biomass energy systems: Environmental benefits and challenges, *Environmental Science & Technology*, 2021, **55**, 4190-4200.
- [9] P. Suwannaket, P. Prompanya, Mapping and quantification of agricultural biomass resources for bioenergy in Thailand, *Thai Journal of Agricultural Science*, 2020, **53**, 450-465.
- [10] N. Techapanya, K. Boonsong, Research and development landscape of biomass conversion technologies in Thailand: Current status and future outlook, *Energy Policy Perspectives*, 2022, **10**, 78-92.
- [11] S. J. Lim, W. K. Tan, Biomass valorization for circular economy and energy security: A review of recent advancements, *Resources, Conservation and Recycling*, 2023, **190**, 106720, doi: 10.1016/j.resconrec.2023.106720.
- [12] F. Chen, G. Li, Strategic pathways for accelerating biomass energy deployment: Technological innovations and policy implications, *Sustainable Energy Technologies and Assessments*, 2022, **53**, 102715, doi: 10.1016/j.seta.2022.102715.
- [13] J. D. Smith, P. Q. Taylor, The ancient roots of energy: A historical review of biomass utilization, *Journal of Energy History*, 2018, **5**, 112-125.
- [14] R. Kumar, V. Singh, The continuing relevance of biomass energy in rural electrification and poverty alleviation, *Sustainable Development Journal*, 2020, **28**, 678-690.
- [15] L. M. Davies, K. R. O'Connell, Household energy consumption patterns in sub-Saharan Africa: The enduring role of traditional biomass, *Energy for Sustainable Development*, 2019, **51**, 45-56.
- [16] E. Garcia, M. Rodriguez, A comprehensive review of thermochemical and biochemical pathways for biomass energy conversion, *Renewable Energy Research*, 2021, **161**, 103987, doi: 10.1016/j.renene.2021.103987.
- [17] H. Chen, W. Li, Thermal applications of biomass in developing countries: Cooking, heating, and small-scale industrial uses, *Biomass and Bioenergy Reviews*, 2018, **112**, 1-15.
- [18] Global Forest Watch, Impact of deforestation on traditional biomass energy sources and rural livelihoods, *Environmental Conservation Journal*, 2022, **49**, 200-215.
- [19] Q. Wang, Y. Zhang, Strategies for enhancing the energy efficiency of biomass utilization systems: A review, *Journal of Energy Efficiency*, 2020, **13**, 1150-1165.
- [20] P. Prasert, T. Suparerk, The role of coconut cultivation in Thailand's agricultural economy and rural development, *Thai Journal of Agricultural Economics*, 2021, **38**, 45-60.
- [21] A. Singh, B. Verma, Valorization of coconut industry by-products: A review of waste-to-energy applications, *Waste Management Bulletin*, 2019, **98**, 10-25.
- [22] B. Indrajit, K. Suraj, Physico-chemical and thermal characteristics of coconut shell waste for energy recovery, *Journal of Applied Energy*, 2022, **20**, 301-315.
- [23] S. Y. Lim, W. K. Tan, Production and characterization of briquettes from coconut shell and their energy properties, *Biomass Conversion and Biorefinery*, 2020, **10**, 401-415.
- [24] M. A. Hassan, S. A. Rashid, Review on the availability and utilization of oil palm biomass in Malaysia and Thailand, *Journal of Bioenergy Research*, 2021, **14**, 500-512.
- [25] S. B. Azmi, Z. Yaakob, Co-briquetting of coconut shell and oil palm empty fruit bunch: Effects on calorific value and combustion characteristics, *Sustainable Energy Technologies and Assessments*, 2023, **57**, 102987, doi: 10.1016/j.seta.2023.102987.
- [26] M. Devi, S. Kumar, Optimization of blending ratios for

- biomass briquettes to achieve improved fuel quality for domestic and industrial applications, *Applied Energy*, 2022, **320**, 119280, doi: 10.1016/j.apenergy.2022.119280.
- [27] ASTM International, ASTM D3172-13 Standard practice for proximate analysis of coal and coke, West Conshohocken, PA, 2013.
- [28] ASTM International, ASTM D5865 / D5865M-19 Standard test method for gross calorific value of coal and coke, West Conshohocken, PA, 2019.
- [29] ASTM International, ASTM D3176-15 Standard practice for ultimate analysis of coal and coke, West Conshohocken, PA, 2015.
- [30] Y. H. Yang, J. Y. Fang, Y. D. Pan, C. J. Ji, Aboveground biomass in Tibetan grasslands, *Journal of Arid Environments*, 2009, **73**, 91-95, doi: 10.1016/j.jaridenv.2008.09.027.
- [31] T. Sutrisno, W. Anggono, F. D. Sprianto, A. W. Kasrun, I. H. Siahaan, The effects of particle size and pressure on the combustion characteristics of cerbera manghasleaf briquettes, *ARPN Journal of Engineering and Applied Sciences*, 2017, **12**, 931-936.
- [32] S. Suwondo, R. D. Ikhsan, L. Iriany, S. Gultom, The effect of carbonization temperature on the characteristics of activated carbon from palm kernel shells, *Journal of Physics: Conference Series*, 2017, **801**, 012028, doi: 10.1088/1742-6596/801/1/012028.
- [33] S. Rezanía, M. Ponraj, M. F. M. Din, A. R. Songip, F. M. Sairan, S. Chelliapan, The diverse applications of water hyacinth with main focus on sustainable energy and production for new era: an overview, *Renewable and Sustainable Energy Reviews*, 2015, **41**, 943-954, doi: 10.1016/j.rser.2014.09.006.
- [34] A. Demirbas, Combustion characteristics of different biomass fuels, *Progress in Energy and Combustion Science*, 2004, **30**, 219-230, doi: 10.1016/j.peccs.2003.10.004.
- [35] D. Lv, C. Liang, C. Li, S. Chen, F. Cao, C. Yang, Q. Feng, Effect of pyrolysis temperature on biomass fuel properties of municipal solid waste for energy recovery, *Energy Conversion and Management*, 2020, **220**, 113098, doi: 10.1016/j.enconman.2020.113098.
- [36] M. Thabuot, T. Pagketanang, K. Panyacharoen, P. Mongkut, P. Wongwicha, Effect of applied pressure and binder proportion on the fuel properties of holey bio-briquettes, *Energy Procedia*, 2015, **79**, 890-895, doi: 10.1016/j.egypro.2015.11.583.
- [37] K. Jindo, T. Mizumoto, Y. Sawada, M. A. Sanchez-Monedero, T. Sonoki, Physical and chemical characterization of biochars derived from different biomass materials and their application to retain nutrients, *Journal of Agricultural and Food Chemistry*, 2014, **62**, 10214-10221, doi: 10.1021/jf503008h.
- [38] I. Fonts, G. Gea, M. Azuara, J. Ábrego, J. Arauzo, Sewage sludge pyrolysis for liquid production: a review, *Renewable and Sustainable Energy Reviews*, 2012, **16**, 2781-2805, doi: 10.1016/j.rser.2012.02.070.
- [39] W. Chen, K. Li, Z. Yang, J. Chen, Effects of pyrolysis temperature on the physicochemical properties and adsorption performance of biochar derived from cotton stalk, *Bioresource Technology*, 2017, **241**, 280-288, doi: 10.1016/j.biortech.2017.05.021.
- [40] S. V. Vassilev, D. Baxter, L. K. Andersen, C. G. Vassileva, An overview of the composition and application of biomass ash, *Fuel*, 2013, **105**, 19-39, doi: 10.1016/j.fuel.2012.10.001.
- [41] L. Wang, J. Lei, B. Qu, Effect of carbonization temperature on the characteristics of biochar derived from agricultural wastes, *Bioresource Technology*, 2012, **125**, 242-247, doi: 10.1016/j.biortech.2012.09.020.
- [42] H. Yang, R. Yan, H. Chen, D. H. Lee, C. Zheng, Characteristics of hemicellulose, cellulose and lignin pyrolysis, *Fuel*, 2007, **86**, 1781-1788, doi: 10.1016/j.fuel.2006.12.013.
- [43] M. J. Antal, M. Grønli, The art, science, and technology of charcoal production, *Industrial & Engineering Chemistry Research*, 2003, **42**, 1619-1640, doi: 10.1021/ie0207919.
- [44] Y. Shen, P. Zhao, D. Ma, W. Yi, Pyrolysis of agricultural residues for biochar production: Effect of pyrolysis parameters on product yield and characteristics, *Journal of Cleaner Production*, 2015, **86**, 371-377, doi: 10.1016/j.jclepro.2014.07.039.
- [45] J. Prasityousil, A. Muenjina, Properties of solid fuel briquettes produced from rejected material of municipal waste composting, *Procedia Environmental Sciences*, 2013, **17**, 603-610, doi: 10.1016/j.proenv.2013.02.076.
- [46] S. J. Mitchual, K. Frimpong-Mensah, N. A. Darkwa, Evaluation of fuel properties of six tropical hardwood timber species for briquettes, *Journal of Sustainable Bioenergy Systems*, 2014, **4**, 1-9, doi: 10.4236/jsbs.2014.41001.
- [47] A. K. Maciejewska, H. Veringa, J. P. M. Sanders, S. D. Peteves, Co-firing of biomass with coal: Constraints and role of biomass pretreatment, *Office for Official Publications of the European Communities*, Scientific Report, Luxembourg, 2006, ISBN - 9789279029899-113.
- [48] K. B. Deepak, N. A. Njanesh, Investigation of areca leaves as a biomass fuel by the method of briquetting, *International Journal of Mechanical Engineering (IJME)*, 2015, **3**, 16-21.
- [49] R. Ciriminna, M. Lomeli-Rodriguez, P. Demma Carà, J. A. Lopez-Sanchez, M. Pagliaro, Limonene: a versatile chemical of the bioeconomy, *Chemical Communications*, 2014, **50**, 15288-15296, doi: 10.1039/c4cc06147k.
- [50] C. Sheng, J. L. T. Azevedo, Estimating the higher heating value of biomass fuels from basic analysis data, *Biomass and Bioenergy*, 2005, **28**, 499-507, doi: 10.1016/j.biombioe.2004.11.008.
- [51] S. H. Sanger, A. G. Mohod, Y. P. Khandetode, H. Y. Shrirame, A. S. Deshmukh, Study of carbonization for cashew nutshell, *Research Journal of Chemical Sciences*, 2011, **1**, 43-55.
- [52] O. O. Oladeji, O. I. Ejike, A. G. Adeniyi, Production and characterization of briquettes from coconut shell and palm kernel shell blends, *Journal of Energy Technology and Environmental Protection*, 2017, **1**, 1-8.
- [53] S. Supramono, D. S. Handayani, I. Puspitasari, The effect of raw material composition and compaction pressure on the quality of briquette from rice husk and sawdust, *International Journal of Renewable Energy Development (IJRED)*, 2017, **6**, 209-216, doi: 10.14710/ijred.6.3.209-216.

[54] A. Garcia-Maraver, D. Salvachúa, M. J. Martínez, L. F. Diaz, M. Zamorano, Analysis of the relation between the cellulose, hemicellulose and lignin content and the thermal behavior of residual biomass from olive trees, *Waste Management*, 2013, **33**, 2245-2249, doi: 10.1016/j.wasman.2013.07.010.

[55] N. Kaliyan, R. Vance Morey, Factors affecting strength and durability of densified biomass products, *Biomass and Bioenergy*, 2009, **33**, 337-359, doi: 10.1016/j.biombioe.2008.08.005.

Publisher's Note: Engineered Science Publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access

This article is licensed under a Creative Commons Attribution 4.0 International License, which permits the use, sharing, adaptation, distribution and reproduction in any medium or format, as long as appropriate credit to the original author(s) and the source is given by providing a link to the Creative Commons license and changes need to be indicated if there are any. The images or other third-party material in this article are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit <http://creativecommons.org/licenses/by/4.0/>.

©The Author(s) 2025.