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Optimization of Characterization and Carbonization Temperature of Orange Peel Waste-Derived Biobriquettes for Sustainable Energy Applications

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Abstract

The rising need for sustainable energy and the escalating buildup of organic waste have spurred the creation of renewable fuels derived from biomass. Orange peel waste is a plentiful agricultural by-product that is high in lignocellulosic materials, positioning it as a valuable source for biobriquette manufacturing. This research sought to investigate the effect of carbonization temperature on the energy performance of biobriquettes made from orange peel waste. A laboratory experiment was conducted with four carbonization temperatures: 300°C, 400°C, 500°C, and 600°C. The produced biochar was converted into biobriquettes and analyzed for moisture content, ash content, volatile matter, fixed carbon content, density, combustion rate, and calorific value. Data were evaluated through one-way analysis of variance (ANOVA) accompanied by Tukey's HSD test at a 95% confidence interval. ANOVA and Tukey's HSD results showed that carbonization temperature significantly affected all measured parameters ($p < 0.05$). Increasing the carbonization temperature decreased the moisture content from 8.72% to 4.26% and the volatile matter content from 31.45% to 18.62%, while increasing the fixed carbon content from 54.71% to 69.59% and the calorific value from 19.21 MJ/kg to 27.41 MJ/kg. The 600°C treatment produced significantly superior fuel properties because higher temperatures promoted more complete thermochemical decomposition and carbon enrichment, resulting in higher fixed carbon, lower volatile matter, and greater calorific value. These results indicate that orange peel waste can be successfully converted into premium biobriquettes and that carbonization temperature is a crucial element in improving

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fuel efficiency. This study emphasizes the potential of biobriquettes made from orange peel waste as a sustainable and environmentally friendly energy source, and encourages waste utilization and circular economy initiatives.

Keywords: Optimization, Carbonization Temperature, Energy Performance, Orange Peel Biobriquettes, Sustainable Energy Application

1. Introduction

The increasing demand for energy worldwide, coupled with dwindling fossil fuel supplies and growing environmental concerns, has driven the search for sustainable and renewable energy alternatives (Manurung et al., 2025). Fossil fuels continue to be the primary source of energy worldwide; however, their widespread use significantly increases greenhouse gas emissions, climate change, and environmental degradation. Consequently, the creation of alternative energy sources from renewable biomass has emerged as a crucial approach to achieving a sustainable energy system and reducing dependence on non-renewable fuels (Alexander et al., 2025).

Biomass is considered a very promising renewable energy source due to its high availability, renewability, potential carbon neutrality, and wide availability. Agricultural and agro-industrial by-products, especially, present substantial prospects for transformation into valuable energy products (Aleman-Ramirez et al., 2024). Among different biomass conversion methods, biobriquetting has proven to be an efficient technique for converting low-density biomass residues into dense solid fuels that enhance handling, transportation, storage, and combustion properties (Sinaga et al., 2024). Biobriquettes have gained considerable attention because they can serve as environmentally friendly substitutes for conventional charcoal and fossil-based fuels while simultaneously addressing waste management challenges (Sirait et al., 2024).

Indonesia ranks among the top global producers of citrus fruits, resulting in significant amounts of orange peel waste from homes, local markets, eateries, juice-processing facilities, and food manufacturing industries (Silaban et al., 2025). Orange peel waste is frequently thrown away without effective use, resulting in environmental concerns like bad smells, methane release from decay, and rising levels of organic waste buildup (Siahaan et al, 2023). Nonetheless, orange peels have significant quantities of cellulose, hemicellulose, and lignin, which are vital lignocellulosic elements appropriate for thermochemical conversion methods, such as carbonization and briquette manufacturing (Shaker et al., 2023). Consequently, transforming orange peel waste into biobriquettes offers an appealing option for renewable energy production and effective waste management (Sinurat et al., 2026).

The carbonization process significantly affects the quality of biobriquettes made from biomass. Carbonization transforms raw biomass into carbon-dense biochar via thermal breakdown in low-oxygen environments (Samosir et al., 2026). The temperature of carbonization is essential in influencing the physicochemical characteristics of the produced biochar, such as fixed carbon

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content, volatile matter, ash content, porosity, and calorific value (Pardede et al., 2026). Typically, elevating carbonization temperature improves carbon content and energy density, while decreasing moisture and volatile substances (Susanti et al., 2025). Nonetheless, extremely high temperatures can reduce biochar production and change structural features that influence briquette efficiency (Sirait et al., 2021). As a result, determining the ideal carbonization temperature is crucial for generating high-quality biobriquettes with excellent energy characteristics (Barus et al., 2024).

Several studies have investigated the production of biobriquettes from various agricultural wastes such as coconut shells, rice husks, corn cobs, coffee husks, and banana peels (Abdillah et al., 2024). These investigations commonly indicated that carbonization temperature considerably influences fuel quality factors, such as calorific value, combustion efficiency, and mechanical strength (Siahaan et al., 2026). However, despite these advances, previous studies have predominantly focused on commonly utilized lignocellulosic biomass, while the potential of orange peel waste remains comparatively underexplored. Existing studies on orange peel biobriquettes are generally limited to evaluating basic fuel properties, with insufficient attention given to the systematic optimization of carbonization temperature and its relationship with changes in physicochemical characteristics that ultimately determine fuel performance. (Sinaga et al., 2026). Moreover, comparative investigations integrating moisture content, ash content, volatile matter, fixed carbon, and calorific value under different carbonization temperatures using a comprehensive statistical approach are still scarce (Pardede et al, 2026). This lack of integrated analysis represents an important research gap, limiting the understanding of the mechanisms by which carbonization temperature governs the quality and energy performance of orange peel biobriquettes (Pane et al., 2025). Therefore, this study seeks to address this gap by providing a systematic evaluation of the influence of carbonization temperature on the physicochemical and energy characteristics of orange peel biobriquettes, thereby contributing new scientific evidence for optimizing the utilization of citrus waste as a sustainable solid biofuel (Sinurat et al., 2024).

In the context of promoting sustainable energy and a circular economy, utilizing orange peel waste as a renewable solid fuel offers significant environmental and economic benefits (Sitinjak et al., 2024). Converting this neglected biomass waste into biobriquettes can address various waste management challenges, improve resource efficiency, and provide an alternative energy source for households and small-scale industries (Alexander et al., 2026). Furthermore, improved carbonization methods can improve the quality and competitiveness of biomass-derived solid fuels in the renewable energy industry (Alexander et al., 2024).

Therefore, this study aims to systematically investigate the effect of different carbonization temperatures on the physicochemical and energy performance of orange peel biobriquettes in order to identify the optimum carbonization condition and to explain the relationship between carbonization temperature and fuel quality characteristics(Alexander et al., 2025). This study will investigate the impact of different carbonization temperatures on key fuel quality parameters, including moisture content, ash content, volatile matter content, fixed carbon content, and calorific value (Saragih et al., 2025). Furthermore, the findings are expected to provide a scientific basis for optimizing the production of high-quality orange peel biobriquettes and to enrich the current understanding of biomass carbonization processes for sustainable bioenergy applications (Donald

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et al., 2022). It is hoped that the results of this study will provide scientific insights into the efficient utilization of citrus waste biomass and support the development of sustainable energy technologies based on renewable resources (Sirait, 2025). Furthermore, this research supports national and international initiatives focused on waste management, energy diversification, and achieving sustainable development goals through the use of environmentally friendly solid biomass (Silaen et al., 2025).

2. Methods

Research Design

This study used a laboratory experimental approach to investigate the effect of carbonization temperature on the energy performance characteristics of biobriquettes produced from orange peel waste. A completely randomized design (CRD) was used, including four carbonization temperature treatments and three replications for each treatment (Silaban et al., 2025). Each treatment consisted of three independently prepared biochar batches, and each analytical parameter was measured in triplicate (n = 3), resulting in a total of 36 analytical observations. The allocation of samples to each treatment was randomized to minimize experimental bias and ensure the independence of observations.

Carbonization Temperature Treatments

Treatment	Carbonization Temperature (°C)
T1	300
T2	400
T3	500
T4	600

Each treatment was repeated three times, resulting in a total of 12 experimental units. The selected carbonization temperatures (300–600°C) were chosen based on previous biomass carbonization studies demonstrating that this range adequately represents the transition from incomplete carbonization to highly carbonized biochar, thereby allowing evaluation of temperature-dependent changes in physicochemical and fuel properties while avoiding excessive biomass degradation at temperatures above 600°C.

Materials and Equipment

Materials

The resources utilized in this research comprised:

- Recently gathered orange peel waste from nearby fruit markets;
- Tapioca flour serving as a natural adhesive;
- Purified water.
- Gear

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Equipment

- Drying chamber
- Furnace for carbonization
- Mill
- Strainer (60 mesh)
- Heating furnace equipped with a programmable temperature controller
- Hydraulic briquette machine
- Precision balance
- Desiccator
- Muffle furnace
- Bomb calorimeter
- Digital Vernier caliper for briquette dimension measurement

Preparation of Orange Peel Waste

Fresh orange peels are thoroughly cleaned with tap water to remove dirt and impurities. They are then cut into small pieces measuring approximately 2–3 cm and dried in an oven at 105°C for 24 hours to reduce the air content. The dried orange peels are stored in a sealed container before being carbonized (Pardede et al., 2025).

Carbonization Process

The dried orange peel samples underwent carbonization in a lab furnace with limited oxygen conditions. The furnace temperature was increased from room temperature to the target temperature at a controlled heating rate of 10°C/min. Carbonization was conducted at four different temperatures (300°C, 400°C, 500°C, and 600°C) for a period of 2 hours (Alexander et al., 2024). The selected temperatures were maintained continuously throughout the holding period to ensure complete thermal decomposition of the biomass. After carbonization, the furnace was allowed to cool naturally until approximately 100°C before the biochar was transferred to a desiccator. The biochar was subsequently cooled in the desiccator for approximately 24 hours until reaching room temperature to prevent oxidation and moisture absorption.(Madu et al., 2026).

The produced biochar was measured to assess its yield using the following equation:

$$\textbf{Biochar Yield} = \frac{Mass\ of\ Biochar}{Initial\ Dry\ Biomass\ Mass}\ x\ 100\%$$

The biochar yield was recorded for each treatment to evaluate the influence of carbonization temperature on solid product recovery.

Biobriquette Preparation

The biochar made from carbonized orange peel was sifted through a 60-mesh sieve to achieve a consistent particle size. A solution of tapioca starch was made by mixing tapioca flour with hot water to reach a binder concentration of 10% (w/w). The biochar powder was combined completely

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with the binder until a uniform mixture was achieved. The blend was subsequently compacted with a hydraulic briquette press under a constant pressing pressure of approximately 10 MPa for 60 second cylindrical briquettes with a diameter of approximately 3.0 cm, a height of 4.0 cm, and an average mass of 25–30 g per briquettes. The briquettes were dried in an oven at 105°C for 4 hours and kept in a desiccator before analysis (Pardede et al., 2024). Prior to testing, all briquettes were conditioned at room temperature for 24 hours to ensure moisture equilibrium.

Characterization of Biobriquettes

Moisture Content Analysis

Moisture content was determined according to ASTM D3173. Approximately 1.0 ± 0.01 g of briquette sample was dried at 105°C until a constant weight was achieved. Each measurement was conducted in triplicate.

$$Moisture\ Content\ (\%) = \frac{W_1 - W_2}{W_1} \times 100$$

where:
W_1 = initial sample weight (g)
W_2 = dried sample weight (g)

Ash Content Analysis

Ash content was measured according to ASTM D3174. Approximately 1.0 ± 0.01 g of Samples were combusted in a muffle furnace at 750°C for 4 hours. All measurements were performed in triplicate

$$Ash\ Content\ (\%) = \frac{W_a}{W_s} \times 100$$

where:
W_1 = weight of ash residue (g)
W_2 = weight of sample (g)

Volatile Matter Analysis

Volatile matter was determined following ASTM D3175. Samples were heated at 950°C for 7 minutes in a covered crucible. Approximately 1.0 ± 0.01 g of sample was used for each determination, with three replicate measurements conducted per treatment.

$$Volatile\ Matter\ (\%) = \frac{W_2 - W_3}{W_1} \times 100$$

where:
W_1 = initial sample weight (g)
W_2 = oven-dried sample weight (g)
W_3 = weight after volatile matter determination (g)

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Fixed Carbon Content
Fixed carbon content was calculated by difference:

$$Fixed\ Carbon\ (\%) = 100 - (MC + AC + VM)$$

where:
MC = Moisture Content (%)
AC = Ash Content (%)
VM = Volatile Matter (%)

Calorific Value Analysis
The calorific value of biobriquettes was determined using a Bomb Calorimeter according to ASTM D5865. Approximately 1 g of finely ground briquette sample was used for each analysis, and each treatment was analyzed in triplicate. Results were expressed in MJ/kg.

Density Determination
The density of biobriquettes was calculated using:

$$Density = \frac{Mass}{Volume}$$

where:

- Density (g/cm³)
- Mass (g)
- Volume (cm³)

The dimensions of each briquette were measured using a digital Vernier caliper with an accuracy of 0.01 mm.

Combustion Rate Test
Combustion rate was determined by measuring the mass loss during combustion.

$$Combustion\ Rate = \frac{Initial\ Mass - Final\ Mass}{Combustion\ Time}$$

expressed in g/min.
Each briquette was ignited under identical laboratory conditions, and the combustion rate was calculated from the decrease in briquette mass over the total combustion time. Measurements were performed in triplicate and expressed in g/min.

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Data Analysis

All experimental data were analyzed using IBM SPSS Statistics software.
Descriptive statistics, including mean values and standard deviations, were calculated for all measured parameters. Prior to hypothesis testing, data normality was assessed using the Shapiro–Wilk test, while homogeneity of variance was evaluated using Levene's test.
A one-way analysis of variance (ANOVA) was performed to evaluate the effect of carbonization temperature on moisture content, ash content, volatile matter, fixed carbon, density, combustion rate, calorific value, and biochar yield. Significant differences between treatment means were then examined using a post hoc Tukey's Honestly Significant Difference (HSD) test at the 95% significance level. ($p < 0.05$) (Amelia et al., 2025). The results are presented as mean ± standard deviation (SD), and all statistical analyses were performed using a significance level of $\alpha = 0.05$.

3. Result and Discussion

Results

Effect of Carbonization Temperature on Moisture Content

The moisture content of orange peel waste-derived biobriquettes decreased with increasing carbonization temperature (Table 1). The lowest moisture content was observed in biobriquettes carbonized at 600°C, while the highest moisture content was recorded at 300°C.

Table 1. Moisture Content of Biobriquettes at Different Carbonization Temperatures

Carbonization Temperature (°C)	Moisture Content (%)
300	8.72 ± 0.24
400	7.11 ± 0.19
500	5.84 ± 0.17
600	4.26 ± 0.13

The decrease in moisture content results from the gradual elimination of bound water and volatile substances during thermal decomposition. Increased carbonization temperatures promote enhanced dehydration, leading to a more stable and energy-rich fuel. Values for moisture content found in this study adhered to the Indonesian National Standard (SNI), suggesting a moisture content of under 8% for quality briquettes.

Effect of Carbonization Temperature on Ash Content

The ash content exhibited an increasing trend with rising carbonization temperature (Table 2).

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Table 2. Ash Content of Biobriquettes at Different Carbonization Temperatures

Carbonization Temperature (°C)	Ash Content (%)
300	5.12 ± 0.16
400	5.89 ± 0.18
500	6.74 ± 0.21
600	7.53 ± 0.25

The rise in ash content relates to the accumulation of inorganic minerals following the breakdown of organic matter during carbonization. Despite ash playing a role in residue creation post-combustion, the recorded values stayed within the permissible limits for biomass briquettes.

Effect of Carbonization Temperature on Volatile Matter

Volatile matter content decreased significantly as carbonization temperature increased (Table 3).

Carbonization Temperature (°C)	Volatile Content (%)
300	31.45 ± 0.92
400	26.71 ± 0.83
500	22.38 ± 0.75
600	18.62 ± 0.64

The reduction in volatile matter indicates the thermal breakdown of hemicellulose, cellulose, and lignin components. Reduced volatile matter typically enhances combustion stability and raises fixed carbon levels.

Effect of Carbonization Temperature on Fixed Carbon Content

Fixed carbon content increased substantially with increasing carbonization temperature (Table 4).

Table 4. Fixed Carbon Content of Biobriquettes

Carbonization Temperature (°C)	Fixed Carbon (%)
300	54.71 ± 1.12
400	60.29 ± 1.05
500	65.04 ± 1.18
600	69.59 ± 1.26

The rise in fixed carbon signifies improved carbon enrichment throughout carbonization. Fixed carbon is a key factor as it directly influences extended combustion time and increased energy production.

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Effect of Carbonization Temperature on Density

The density of biobriquettes increased slightly with increasing carbonization temperature (Table 5).

Table 5. Density of Orange Peel Biobriquettes

Carbonization Temperature (°C)	Fixed Carbon (%)
300	0.78 ± 0.03
400	0.82 ± 0.02
500	0.85 ± 0.02
600	0.88 ± 0.03

Higher density indicates better particle packing and improved fuel quality. Denser briquettes typically exhibit longer burn times and better handling characteristics.

Effect of Carbonization Temperature on Combustion Rate

The rate of combustion diminished as the carbonization temperature rose (Table 6).

Table 6. Combustion Rate of Biobriquettes

Carbonization Temperature (°C)	Combustion Rate (g/min)
300	0.61 ± 0.02^{a}
400	0.54 ± 0.02^{b}
500	0.47 ± 0.01^{c}
600	0.42 ± 0.01^{d}

ANOVA: $F = 58.42$, $p < 0.001$

Tukey HSD: Different superscript letters indicate significant differences ($p < 0.05$).

Combustion rate decreased significantly with increasing carbonization temperature (ANOVA, $p < 0.001$). Tukey's HSD test showed that all treatments differed significantly from one another, indicating that progressively higher temperatures consistently reduced combustion rate. This trend demonstrates that carbonization substantially modifies combustion behavior through changes in biomass structure.

Effect of Carbonization Temperature on Calorific Value

The calorific value rose significantly with higher carbonization temperatures (Table 7).

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Table 7. Calorific Value of Orange Peel Waste-Derived Biobriquettes

Carbonization Temperature (°C)	Calorific Value (MJ/kg)
300	19.21 ± 0.44^{a}
400	22.36 ± 0.51^{b}
500	25.08 ± 0.56^{c}
600	27.41 ± 0.63^{d}

ANOVA: $F = 96.85$, $p < 0.001$
Tukey HSD: Different superscript letters indicate significant differences ($p < 0.05$).

Calorific value increased significantly with increasing carbonization temperature (ANOVA, $p < 0.001$). Tukey's HSD analysis confirmed significant differences among all treatment groups. The highest heating value obtained at 600°C indicates that carbonization effectively enhanced the energy density of orange peel biomass by increasing carbon concentration while reducing moisture and volatile compounds.

Statistical Analysis

One-way ANOVA analysis revealed that carbonization temperature had a significant effect on all measured parameters, including air content, ash content, volatile matter, fixed carbon, density, combustion rate, and heating value ($p < 0.05$). Subsequent Tukey HSD analysis showed significant variations between all treatment groups. The 600°C treatment consistently showed the best fuel properties, as indicated by:

- Lowest moisture content (4.26%);
- Lowest volatile matter (18.62%);
- Highest fixed carbon (69.59%);
- Highest density (0.88 g/cm³);
- Lowest combustion rate (0.42 g/min);
- Highest calorific value (27.41 MJ/kg).

These findings demonstrate that increasing carbonization temperature enhances the physicochemical and energy properties of orange peel waste-derived biobriquettes.

The one-way ANOVA revealed that carbonization temperature significantly affected all measured properties of orange peel waste-derived biobriquettes ($p < 0.05$). Subsequent Tukey's HSD multiple comparison test demonstrated that each carbonization temperature treatment differed significantly from the others for moisture content, volatile matter, fixed carbon, combustion rate, and calorific value. The 600°C treatment consistently exhibited the most favorable fuel characteristics, indicating that increasing carbonization temperature promoted progressive thermochemical conversion of biomass into a carbon-rich solid fuel. These statistically significant differences confirm that the observed improvements resulted from the carbonization treatment rather than random experimental variation.

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Optimization of Carbonization Temperature for Sustainable Energy Applications

After conducting a comprehensive assessment of fuel quality elements, a carbonization temperature of 600°C was recognized as the ideal condition for producing superior biobriquettes from orange peel waste. At this temperature, the briquettes demonstrated improved energy efficiency, with higher calorific value, increased fixed carbon content, and improved combustion stability. The findings indicate that orange peel waste presents considerable potential as a renewable biomass source for sustainable energy generation. Converting citrus processing waste into high-performance biobriquettes contributes to waste valorization and supports the principles of the circular economy while enhancing renewable energy development. As a result, biobriquettes created from orange peels provide a promising alternative solid fuel for home and small-scale industrial applications.

Discussion

Recent research shows that carbonization temperature has a significant impact on the physicochemical properties and energy efficiency of bio-briquettes made from orange peel waste (Indah et al., 2024). Variations in carbonization temperature affect the thermal degradation properties of biomass constituents, resulting in changes in moisture content, ash content, volatile matter content, fixed carbon content, combustion rate, and energy value. These findings confirm that carbonization is a critical step in evaluating the quality of solid fuels derived from biomass (Alexander et al., 2025).

Effect of Carbonization Temperature on Moisture Content

The results showed a steady decrease in water content with increasing carbonization temperature from 300°C to 600°C. This effect occurs because higher temperatures increase the evaporation of free water and facilitate the extraction of chemically bound water from the biomass structure. During the carbonization process, the thermal decomposition of hemicellulose and cellulose leads to the release of water vapor and various volatile substances, which consequently reduces the total water content in the final biochar (Silaban et al., 2020).

This phenomenon is primarily governed by thermochemical dehydration and devolatilization reactions. During carbonization, hydroxyl groups (-OH) present in cellulose and hemicellulose are progressively eliminated, while thermal decomposition releases water vapor, carbon dioxide, carbon monoxide, methane, and condensable organic compounds. As temperature increases to 600°C, aromatic carbon structures become dominant, reducing the hydrophilic nature of biochar and preventing subsequent moisture adsorption. Therefore, the decrease in moisture content is not merely a consequence of water evaporation but also reflects fundamental structural changes in the lignocellulosic matrix (Donald et al., 2022). From a fuel design perspective, lower moisture content increases thermal efficiency because less combustion energy is consumed for water evaporation, thereby improving ignition characteristics and net heat output.

Optimal moisture content is crucial in briquette production because excess moisture reduces combustion efficiency and lowers the fuel's effective calorific value. Previous studies on biomass

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briquettes have shown that lower moisture content facilitates ignition, stabilizes the flame, and improves overall combustion efficiency. Consequently, the lower moisture content observed at high carbonization temperatures improves the energy quality of orange peel biomass briquettes (Silaban et al., 2021).

Effect of Carbonization Temperature on Ash Content

An increase in ash content was observed with increasing carbonization temperature. This pattern is frequently observed in biomass carbonization studies and is attributed to the gradual decomposition of organic matter during the thermal process. With the removal of volatile compounds and combustible organic fractions, the concentration of non-combustible mineral components in the remaining biochar increases (Silaban et al., 2021).

Despite the potential negative impact of high ash content on combustion efficiency due to greater residue accumulation, the ash content observed in this study remained within acceptable limits for biomass briquettes. Mineral elements found in orange peel biomass, such as potassium, calcium, and magnesium, may have increased the ash content after combustion. However, the increase in ash content was relatively small compared to the observed increases in calorific value and fixed carbon content (Silaban et al., 2024).

Effect of Carbonization Temperature on Volatile Matter

The significant reduction in volatile matter as carbonization temperature increases indicates enhanced thermal decomposition of biomass components. Volatile matter primarily consists of gases and condensable materials generated from the decomposition of hemicellulose, cellulose, and lignin when subjected to heat. At elevated temperatures, these materials are released from the biomass structure, resulting in a product that contains more carbon (Simatupang et al., 2025). Decreasing volatile matter improves fuel quality by resulting in a cleaner and more uniform combustion process. Briquettes with lower volatile matter generally produce less smoke and demonstrate improved combustion efficiency. Moreover, the reduction in volatile compounds is often associated with an increase in fixed carbon content, enhancing the fuel's energy density (Pardede et al., 2024). The progressive decrease in volatile matter is associated with sequential decomposition of biomass polymers. Hemicellulose decomposes predominantly between 200–350°C, cellulose between 300–400°C, whereas lignin degrades gradually over a broader temperature range extending beyond 500°C. Consequently, increasing carbonization temperature removes larger amounts of volatile hydrocarbons and oxygen-containing compounds, leaving behind a thermally stable carbon-rich matrix. This mechanism explains why fixed carbon and calorific value increased simultaneously (Msobi et al., 2026).

Effect of Carbonization Temperature on Fixed Carbon Content

As the carbonization temperature increases, the fixed carbon content increases significantly. This finding aligns with the essential process of biomass carbonization, where the removal of moisture and volatiles increases the carbon content within the biochar framework. Fixed carbon is considered an important metric of fuel quality because it indicates the component that provides

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consistent heat production during combustion. Briquettes containing more fixed carbon typically burn longer and offer more consistent heat output. The maximum fixed carbon content recorded at 600°C indicates that this temperature successfully increases carbon accumulation and improves the fuel characteristics of briquettes made from orange peels. The increase in fixed carbon also indicates the transformation of biomass into a substance with characteristics similar to traditional charcoal, increasing its potential as a viable alternative renewable energy source (Alexander et al., 2025).

The increase in fixed carbon results from progressive carbon enrichment during pyrolysis. As hydrogen- and oxygen-containing functional groups are removed through dehydration, decarboxylation, decarbonylation, and devolatilization reactions, the relative proportion of elemental carbon increases substantially. Simultaneously, aromatic ring condensation produces a more ordered carbon structure with higher thermal stability. These thermochemical transformations explain the significant improvement in combustion duration and heating value observed at elevated carbonization temperatures. This finding has important implications for fuel engineering because briquettes with higher fixed carbon generally exhibit longer combustion duration, greater energy density, and more stable heat release, making them more suitable for domestic and industrial thermal applications (Msobi et al., 2026).

Effect of Carbonization Temperature on Density and Combustion Behavior

Increasing carbonization temperature significantly modified both the physical structure and combustion behavior of the briquettes. Higher temperatures promoted greater shrinkage of biomass particles while simultaneously increasing carbon concentration, resulting in improved particle packing during briquetting. Consequently, briquette density increased gradually with temperature. Statistical analysis confirmed significant differences among treatments (ANOVA, $p < 0.05$).

The reduction in combustion rate can be explained by restricted oxygen diffusion within denser briquettes. Increased density reduces internal pore connectivity, slowing oxygen penetration into the combustion zone. As oxidation reactions become diffusion-controlled rather than reaction-controlled, combustion proceeds more slowly but more uniformly. Such combustion behavior is desirable because it prolongs burning duration and provides more stable heat release (Sirait et al., 2023). From a fuel design perspective, balancing density and combustion rate is essential. Excessively porous briquettes burn rapidly and waste fuel, whereas excessively dense briquettes may hinder ignition. Therefore, the density achieved at 600°C appears to provide an appropriate compromise between combustion stability and energy efficiency (Alexander et al., 2025).

Effect of Carbonization Temperature on Calorific Value

Of all the parameters evaluated, the calorific value showed the greatest increase with increasing carbonization temperature. The calorific value increased from 19.21 MJ/kg at 300°C to 27.41 MJ/kg at 600°C, indicating a significant increase in energy content. Several factors can be attributed to this increase (Yunita Sari et al., 2026). First, increasing the carbonization temperature reduces the moisture content, thereby reducing energy losses associated with water evaporation during combustion. Second, the removal of volatile compounds increases the carbon content in the

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briquettes. Third, increasing the fixed carbon content directly leads to an increase in energy storage capacity. The calorific values found in this study are similar to those documented for other high-quality biomass briquettes made from agricultural waste such as coconut shells, corn cobs, and coffee husks. Consequently, orange peel waste shows significant potential as a source for producing renewable solid fuels (Alexander et al., 2024).

The increase in calorific value is fundamentally associated with changes in biomass elemental composition during carbonization. Progressive removal of oxygen-rich compounds increases the carbon-to-oxygen ratio, while aromatic carbon structures formed during secondary pyrolysis possess higher intrinsic energy content. Consequently, the higher heating value observed at 600°C reflects not only moisture reduction but also substantial chemical transformation of lignocellulosic biomass into energy-dense carbonaceous material. The statistical significance obtained from ANOVA and Tukey's HSD analysis confirms that these improvements are systematic rather than incidental. This finding suggests that optimizing carbonization temperature represents an effective engineering strategy for producing high-performance renewable solid fuels with enhanced thermal efficiency (Alexander, Sirait, et al., 2025).

Optimization of Carbonization Temperature

Statistical evaluation validated that carbonization temperature had a significant impact on all measured fuel quality indicators. Of the treatments evaluated, 600°C produced the best blend characteristics, exhibiting the lowest moisture content, the lowest volatile compounds, the highest fixed carbon content, and the highest peak calorific value. The performance improvement observed at 600°C was due to more complete decomposition of biomass components and increased carbon content. At lower temperatures, carbonization may not be fully achieved, leading to increased volatile compound content and decreased energy density. On the other hand, the selected temperature of 600°C offered sufficient thermal energy to increase biochar production while maintaining ash content within acceptable limits. The results indicate that a carbonization temperature of 600°C is suitable for producing high-quality biobriquettes from orange peel waste and could serve as a viable operational standard for future large-scale production (Saragih et al., 2025).

Implications for Sustainable Energy Development

T Converting orange peel waste into biobriquettes offers significant benefits for environmental sustainability and energy production. Households, markets, and the food processing sector generate large amounts of orange peel waste, which is often discarded without further use. Converting this waste into a renewable solid fuel improves waste utilization, minimizes environmental pollution, and supports circular economy initiatives. (Sitorus et al., 2025).

Furthermore, the substantial calorific value and favorable combustion characteristics demonstrated in this study suggest that biobriquettes made from orange peels can act as an efficient substitute for fossil fuels and traditional charcoal. Their use can result in lower greenhouse gas emissions, improve energy security, and support the advancement of sustainable energy. (Zhafira et al., 2023).

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The results of this study highlight the potential of orange peel waste as a largely untapped biomass resource that can contribute to renewable energy generation while addressing organic waste management issues. Consequently, the production of biobriquettes from orange peel waste supports global initiatives for sustainable resource management and the transition to low-carbon energy solutions (Silaban et al., 2024).

4. Conclusion

The research results indicate that the carbonization temperature significantly influences all tested parameters, such as moisture content, ash content, volatile matter, fixed carbon content, density, burning rate, and calorific value.

Increasing the carbonization temperature from 300°C to 600°C resulted in a decrease in moisture content, volatile matter, and burning rate, alongside an increase in ash content, density, fixed carbon content, and calorific value. These changes indicate that raising the carbonization temperature improves biochar quality and enhances the overall fuel characteristics of the resulting bio-briquettes.

Among the treatments evaluated, a carbonization temperature of 600°C yielded the most efficient bio-briquettes, characterized by the lowest moisture content (4.26%), lowest volatile matter (18.62%), highest fixed carbon (69.59%), maximum density (0.88 g/cm³), and highest calorific value (27.41 MJ/kg). These characteristics demonstrate improved combustion efficiency and energy performance compared to bio-briquettes produced at lower carbonization temperatures.

The findings show that orange peel waste is an effective biomass source for producing renewable solid fuel. Through the application of appropriate carbonization techniques, orange peel waste can be converted into high-quality bio-briquettes with superior energy properties, making them ideal for both household use and small-scale industrial needs. This method not only supports sustainable energy advancement but also promotes waste management efforts and the implementation of a circular economy.

In conclusion, employing a carbonization temperature of 600°C is a successful approach to enhancing the energy efficiency of orange peel waste bio-briquettes, while simultaneously strengthening their potential as a sustainable and environmentally friendly energy source.

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