Performance Analysis and Modeling of the Combustion Characteristics of Carbonized Rice Husk Briquettes: Effects of Clay-Binder Ratio and Compaction Level

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Abstract. *This study investigates the combined effects of clay binder ratio and compaction level on the combustion performance of carbonized rice husk briquettes, focusing on ignition time, burning rate, flame duration, peak temperature, and thermal efficiency. Experimental results revealed that moderate clay contents (5–15%) and compaction levels (6–18 mm) significantly enhanced ignition stability, peak combustion temperature (up to ~970 ºC), and burn duration (up to 130 minutes). Moderate clay addition improved briquette strength but slightly reduced thermal efficiency, as the inert clay fraction diluted fuel energy. Low compaction (6 mm) increased porosity and airflow, resulting in rapid ignition and higher peak temperatures suited for quick, intense heating, whereas moderate compaction (12 mm) ensured balanced ignition, stable combustion, and prolonged flame duration. Excessive clay content (>15%) and high compaction (18 mm) reduced combustion efficiency due to increased ash formation and restricted airflow, leading to lower peak temperatures and incomplete combustion. Water boiling tests confirmed that briquettes with 5–10% clay and moderate compaction achieved optimal heat output for household cooking. A third-order polynomial regression model incorporating interaction terms accurately predicted ignition time, peak temperature, and burn duration (R² = 0.900–0.997), effectively capturing nonlinear combustion behavior. The findings provide practical insights for tailoring briquette formulations to diverse cooking requirements—from quick, high-heat applications to long-duration simmering—thereby supporting the development of efficient, sustainable biomass fuels for rural and low-income communities.*

Keywords: Combustion Performance, Peak Temperature, Burn Duration, Thermal Efficiency, Polynomial Regression Model, Sustainable Cooking Fuel

Introduction

As nations increasingly seek to reduce reliance on fossil fuels, the global demand for renewable energy continues to grow, driven by the need to address climate change and promote sustainable, long-term energy security [1]. In many developing countries, the improper management of agricultural residues—such as open-field burning or indiscriminate disposal—poses serious environmental and public health risks. Among these residues, rice husk, which represents approximately 22% of the harvested grain mass, is often discarded as waste, despite its considerable potential as a renewable biomass resource. However, due to its high organic volatile content (around 75%), rice husk presents substantial potential as a renewable energy resource [2]. When carbonized, rice husks form a more stable, energy-dense material suitable for conversion into solid biofuels such as briquettes, pellets, and biochar [3], [4]. These carbonized rice husk briquettes offer a clean, sustainable alternative to firewood and fossil fuels—supporting

environmental protection, mitigating deforestation, and improving energy access in low-resource rural areas [5], [6].

The increasing demand for affordable and sustainable energy in developing regions has further accelerated interest in biomass-based fuels [7]. Rice husk briquettes are especially promising for household and small-scale thermal applications. However, their combustion performance— measured through ignition time, burning rate, flame duration, and thermal efficiency—is highly dependent on production parameters such as binder type and compaction level [8]. Clay soil, commonly used as a natural binder due to its availability and cost-effectiveness, enhances briquette structural integrity and durability [9]. Nevertheless, clay is thermally inert, and increasing its proportion may reduce combustibility and heat output.

Compaction pressure also plays a critical role in shaping briquette performance. Adequate pressure enhances particle bonding and reduces porosity, leading to improved mechanical strength and heat retention. However, excessive compaction can limit airflow and hinder complete combustion, while insufficient pressure results in weak, friable briquettes [10], [11]. Despite the known influence of these factors, few empirical studies have systematically explored the combined effects of clay binder ratio and compaction pressure on the combustion characteristics of carbonized rice husk briquettes [12].

This study seeks to fill existing research gaps by evaluating the thermal performance of carbonized rice husk briquettes produced using varying clay soil binder ratios (0%, 5%, 10%, 15%, and 20%) and compaction pressure levels (6 mm, 12 mm, and 18 mm). Key combustion parameters—burning temperature and combustion duration—are experimentally measured to assess how these production factors influence thermal behavior. To better understand and predict these interactions, polynomial regression models are developed to capture the non-linear relationships between binder content, compaction level, and combustion characteristics. These models, supported by both mathematical equations and graphical outputs, serve as reliable tools for optimizing briquette formulation. The insights gained from this analysis contribute to improving the efficiency, durability, and sustainability of biomass briquettes, particularly in low-resource and energy-insecure settings. Accordingly, the primary objective of this research is to systematically investigate how clay soil binder ratios and compaction pressure levels affect the combustion behavior of carbonized rice husk briquettes. The study further aims to develop and validate predictive models that support the design of high-performance, low-emission biomass fuel suitable for clean energy applications in rural and low-income communities.

Theoretical Background

The combustion performance of biomass briquettes is governed by interrelated thermodynamic, physicochemical, and structural factors that determine energy release, transfer, and sustainability during burning. These factors include material composition, binder type, compaction density, and heat transfer behavior, all of which influence ignition rate, flame stability, and energy yield [13]. Understanding these mechanisms is essential for optimizing the combustion behavior of carbonized rice husk briquettes and similar biofuels. Biomass combustion is a multistage thermochemical process comprising drying, devolatilization, volatile oxidation, and char combustion [14]. In carbonized biomass with low volatile content, such as rice husk char, the process is dominated by heterogeneous oxidation of fixed carbon at the char surface [15]. The reaction rate is primarily controlled by oxygen diffusion, combustion temperature, and char

reactivity, which are influenced by particle size and carbonization conditions. According to the Arrhenius principle, the oxidation rate increases exponentially with temperature; however, excessive compaction or the presence of inert additives can restrict airflow, thereby reducing effective combustion temperature and overall efficiency [16].

Binder type and proportion play a crucial role in influencing the combustion dynamics of biomass briquettes. Clay binders, particularly kaolinite and illite, enhance mechanical strength and cohesion but are thermally inert materials that do not contribute to heat generation [8]. Moderate clay addition (typically 5–15%) improves structural durability and maintains sufficient porosity for effective oxygen diffusion, whereas excessive clay content dilutes the carbon fraction, increases ash formation, and lowers the overall heating value [17]. Moreover, the relatively low thermal conductivity of clay (0.2–1.5 W/m·K) limits internal heat transfer within the briquette matrix, potentially slowing combustion rates [18]. Therefore, optimal binder ratios are required to achieve a balance between mechanical strength and thermal performance. Similarly, compaction pressure strongly affects briquette density, porosity, and air permeability, which together determine oxygen accessibility and combustion intensity. Based on Darcy's and Fick's diffusion principles, excessive compaction reduces pore volume and gas diffusivity, leading to incomplete oxidation, while insufficient pressure weakens structural integrity [19], [20]. An intermediate or moderate compaction level thus provides the best balance, ensuring adequate strength and maintaining efficient air diffusion for effective combustion [21].

Thermal efficiency in biomass briquette combustion is governed by the first law of thermodynamics, where the heat output is $Q = m \cdot c \cdot \Delta T$, represents the effectiveness of energy conversion from chemical to thermal form. Performance indicators such as ignition rate and specific fuel consumption (SFC), typically determined through water boiling tests (WBT), are widely used to assess combustion efficiency [22]. Efficient briquettes produce higher Q values and lower SFC, reflecting improved energy utilization influenced by binder ratio, porosity, and compaction level [23]. Because of the non-linear interactions among structural and compositional parameters, empirical and polynomial regression models are often applied to predict and optimize combustion behavior [24]. Conceptually, combustion performance results from the interplay between binder content, compaction pressure, and porosity. While higher binder ratios enhance structural strength, they can reduce fuel reactivity; similarly, excessive compaction restricts oxygen flow and impairs combustion. Porosity acts as a mediating factor, regulating oxygen diffusion, oxidation rate, and flame temperature. Integrating thermochemical kinetics, porosity theory, and empirical modeling thus provides a comprehensive theoretical framework for optimizing briquette formulation and improving the efficiency and cleanliness of renewable solid fuels.

Materials and Methods

Study Area

The Fogera Plain, situated in the South Gondar Zone of Ethiopia's Amhara Region (between latitudes 11º42' N and 12º03' N, and longitudes 37º25' E and 37º58' E), lies at an altitude ranging from 1,500 to 2,500 meters above sea level. Located roughly 582 kilometers north of Addis Ababa, it is positioned east of Lake Tana along the Bahir Dar–Gondar route. The terrain is mainly flat (76%), with undulating (13%) and mountainous (11%) features. The area experiences moderate temperatures between 10.3 ºC and 18.8 ºC, and receives an average annual rainfall of

approximately 1,284 mm [25]. Fogera plain is a key rice-producing region in Ethiopia, accounting for nearly 70% of the country's total rice yield [26]. This agricultural significance has spurred the expansion of rice processing infrastructure, with over 150 mills operating and an average annual growth rate of 34% observed between 1997 and 2018 [27]. Major rice processing zones include Fogera, Gurafarda, and Gambella, where the processing cycle involves cleaning, parboiling, drying, milling, polishing, and packaging of paddy rice. However, despite the economic benefits of rice cultivation, the disposal of rice husk—a major byproduct—remains a critical environmental issue. Frequently discarded in open areas, burned, or used as low-grade fuel, rice husks contribute to pollution and obstruct drainage systems. During the rainy season, the accumulation of husks can worsen flooding and sanitation problems in urban and semi-urban areas.

Research Materials and Equipments

Carbonized rice husk briquetting presents a sustainable and innovative solution for converting agricultural waste—particularly rice husks—into a renewable energy source. Through carbonization, rice husks are transformed into bio char, providing an eco-friendly alternative to traditional wood-based charcoal and reducing dependence on forest-derived fuels. The briquetting process involves several key components:

1) Carbonizer: This device is designed to convert rice husks into biochar through controlled combustion. It features a pyramid-shaped structure with a square base (56 cm in length) and a height of 25 cm. A 1 cm ventilation hole and a 100 cm-long intake pipe (10 cm diameter) regulate airflow and oxygen levels during carbonization to ensure efficient and clean burning (as shown in **Figure 1(a)**).

2) Hammer Mill: Used to grind the carbonized biochar into fine powder, the hammer mill operates with a manually fed hopper. A screen at the bottom controls the particle size to ensure consistency, while a discharge chute collects the processed powder for further use (as illustrated **in Figure 1(b)**).

(a)   (b)   (c)   (d)

Figure 1. Components for carbonized rice husk briquetting process, (a) carbonizer, (b) hammer miller, (c) mold maker, and (d) mold maker with hydraulic jack [28]

3) Mold Maker: Shown in **Figure 1(c)**, the mold maker consists of a hydraulic jack, a robust metal frame, and a prism-shaped piston that compresses the mixture into briquettes. Each piston measures 3.5 cm × 3.5 cm at the base and 10 cm in height. The system accommodates 36 molds to produce uniform briquette cubes (as indicated in **Figure 1(c)**).

4) Charcoal Cooking Stove: Specially adapted to burn rice husk briquettes, these stoves offer an efficient and clean cooking solution. Designed to optimize combustion, they provide a sustainable and practical heat source, particularly in low-resource settings (as shown in **Figure 1(d)**).

The laboratory experiments used rice husks as the primary raw material and locally available surface clay soil as the binder. Based on the FAO/UNESCO Soil Map analyzed using GIS, the clay is classified as a Haplic Xerosol [29], typical of arid regions, with a weakly developed Ochric A horizon (sandy loam to loam; 10–20% clay, 10–20% silt, 60–80% sand). Although the clay's chemical composition and moisture retention were not determined, these properties may influence combustion, thermal efficiency, and briquette structural integrity, and are recommended as a focus for future research. The equipment used for briquette production and testing included: 1) a precision balance for accurate measurement of materials, 2) a plastic bucket and spade for mixing and blending, 3) a construction spoon for shaping the briquettes, 4) an oven for drying the molded briquettes, and 5) a K-type thermocouple, connected to the SQ2020-1F8 portable universal input data logger, was used for precise temperature monitoring during combustion tests. The SQ2020-1F8 is a versatile and robust data acquisition device capable of accurately recording thermal data under varying experimental conditions [28]. Generally, these components and procedures enabled the systematic production and analysis of carbonized rice husk briquettes, supporting their viability as an efficient and environmentally sound biomass fuel.

Briquette Preparation

The production of carbonized rice husk briquettes was conducted through a systematic and controlled process to ensure consistency, structural integrity, and comparability across different clay-binder ratios and compaction levels. The compaction approach used in this study is consistent with previous biomass briquetting research [30]–[32]. The main processes for carbonized rice husk (CRH) briquette preparation are:

1) Carbonization of Rice Husk: Raw rice husks were sourced from the Fogera National Rice Research and Training Center (FNRRTC) rice processing workshop. To reduce the moisture content to approximately 14%, the husks were sun-dried for two days. Carbonization was carried out using a locally fabricated carbonizer (**Figure 2(a)**), where husks were subjected to slow pyrolysis at 350–450 ºC for 2–3 hours under limited oxygen conditions [33]. The process was considered complete when white smoke subsided and the husks turned uniformly black. The resulting carbonized rice husk (CRH) was cooled (**Figure 2(b)**) and stored in airtight containers to preserve quality and prevent reabsorption of moisture.

2) Size Reduction and Binder Mixing: The cooled bio char was ground into fine powder using a hammer miller (**Figure 2(c)**) to ensure uniform particle size and facilitate binding. For each batch, 2 kg of milled CRH was combined with clay soil at predetermined binder-to-char ratios of 0%, 5%, 10%, 15%, and 20% (by weight of dry mass). To activate the binding process, 2

liters of water (approximately 25–30% of the dry mixture weight) were gradually added. The mixture was manually stirred in plastic basins for 10–15 minutes until a cohesive, homogeneous slurry was achieved (**Figure 2(d)**). This ensured even distribution of both water and binder throughout the CRH matrix [34].

3) Briquetting and Compaction: The moist mixture was placed into prism-shaped metal molds with an internal base of 3.5 cm × 3.5 cm and a height of 10 cm. Compression was applied using a hydraulic jack press, reducing the mixture length by 6 mm, 12 mm, and 18 mm to represent high, medium, and low compaction levels, respectively (**Figure 2(e)**). These compaction levels were chosen to assess the effect of compression force on briquette density and combustion performance, while keeping the mold geometry constant. Similar compaction methods have been widely employed in biomass briquette production to study the influence of pressure on density and combustion characteristics. For example, Oladeji (2010) [30] used a manual hydraulic press to investigate the effect of compaction pressure on the physical and combustion properties of corncob briquettes, while Sotannde et al. (2010) [31] examined sawdust briquettes molded under varying compression levels to optimize fuel performance.

(a)   (b)   (c)   (d)

(e)   (f)

Figure 2. Process of carbonized rice husk briquetting (CRH): (a) carbonization of rice husk, (b) cooling and storage of bio char, (c) bio char grinding using hammer mill, (d) mixing of bio char powder with clay and water, (e) briquette molding using mold maker and hydraulic jack, (f) final bio char charcoal briquettes after drying [28]

4) Fermentation and Drying: After compression, the briquettes were allowed to ferment for 24 hours, a stage that promotes natural microbial activity and partial redistribution of moisture, enhancing inter-particle binding and cohesion [12], [35]. Microbial activity during maturation breaks down soluble carbohydrates and proteins, producing organic acids and polysaccharides that act as natural adhesives, thereby enhancing the bonds between rice husk particles and the clay binder and improving briquette hardness [12]. Fermentation also contributes to improved combustion performance by stabilizing the organic matrix and reducing volatile matter, leading to more uniform ignition and sustained burning [36]. Moreover, the controlled microbial degradation can reduce smoke and carbon monoxide emissions during combustion by facilitating more complete oxidation of carbonized biomass [12]. Excess moisture was drained for 3–5 minutes before transferring the briquettes onto drying trays. The green briquettes were then sun-dried for 7–10 days under ambient conditions (average daytime temperature 25–30 ºC; relative humidity 60–70%) until a constant weight was achieved, indicating complete removal of free moisture and readiness for combustion testing (**Figure 2(f)**).

Thermal Property Evaluation

Thermal performance tests were conducted under controlled laboratory conditions to evaluate the combustion characteristics of carbonized rice husk briquettes. The tests aimed to measure critical thermal parameters that reflect fuel efficiency and combustion behavior. A metallic stove prototype was used as the combustion chamber, and a digital temperature logger was employed to monitor real-time temperature changes throughout the experiments. All measurements were performed in triplicate to ensure accuracy, reliability, and reproducibility. The following thermal properties were assessed:

1) Burning Duration (s): This parameter represents the time required for a briquette to ignite upon exposure to an open flame. It indicates the ease of ignition and was measured using a stopwatch from the moment of flame application to the point of sustained combustion [8].

2) Specific Fuel Consumption (SFC, g/L): SFC is defined as the amount of fuel required to boil one liter of water. It serves as a key indicator of thermal efficiency. The test involved boiling a known volume of water using a fixed mass of briquettes, and the fuel consumed was measured [37].

3) Ignition Rate (kg/hr.): The ignition rate quantifies the rate at which the briquette mass is consumed by fire. It was calculated by measuring the weight loss over time and expressing it as kilograms per hour. This metric reflects the speed at which the fuel is converted into energy and ash [38].

4) A Water Boiling Test (WBT) is a standard method used to evaluate the performance of biomass fuels like briquetted charcoal, particularly in terms of energy efficiency, combustion characteristics, and heat transfer capabilities [39]. WBT tests provided comprehensive insights into the combustion performance of the briquettes under standardized experimental conditions. When we perform a WBT with 300 g of briquetted charcoal, here's a general structure of what the process and results might involve as shown in **Table 1**.

Table 1. Test setup parameters

Parameter	Value
Fuel type	Briquetted charcoal
Fuel mass	300 grams
Pot size	Typically 2 L aluminum cooking pot
Water volume	1 liters
Initial water temperature	Room temperature (~25 ºC)
Test location	Controlled environment (lab)
Fuel type	Briquetted charcoal

Research Design

The experiment employed a Randomized Complete Design (RCD) factorial arrangement with two factors: 1) charcoal-to-clay ratio tested at five levels (0%, 5%, 10%, 15%, and 20% (by weight)), and 2) compression level tested at three levels (6 mm (low), 12 mm (medium), and 18 mm (high)) compression during briquette molding.

This resulted in 15 treatment combinations (5 ratios × 3 compression levels). Each treatment was replicated three times, giving a total of 45 experimental units. Treatments were randomly assigned within each block to minimize the effects of uncontrolled variation. Rice husk charcoal was produced by carbonizing rice husks at 400–600 ºC in a traditional kiln (carbonizer) [39]. The binder used was locally sourced clay soil, air-dried, crushed, and sieved through a 2 mm mesh. The charcoal and clay were mixed with water to form a workable paste, molded into cylindrical briquettes approximately 5 cm in diameter, and compressed to the target length using a hydraulic jack. The briquettes were sun-dried for 48–72 hours, then oven-dried at 105 ºC for 24 hours [40]. Combustion tests were conducted using 300 g of briquettes burned using a household cooking combustion chamber and an aluminum cooking pot with sufficient airflow and thermal insulation. A K-type thermocouple was placed 1 cm above the fuel bed to record temperatures every second until complete burnout.

Data Analysis and Modeling

The effects of clay-binder ratio and compaction level on thermal performance were assessed using descriptive statistics, ANOVA, and polynomial regression. Regression models relating time and temperature, generated using R, SPSS, and Minitab 21, incorporated slope, time, and initial temperature, providing practical guidance for charcoal grilling. Environmental factors, including airflow, humidity, and charcoal type, were controlled throughout the experiments.

Results and Discussion

Physical Properties of Carbonized Rice Husk Briquettes

The combined effects of compaction pressure and biochar-to-clay ratios on the physical and combustion properties of carbonized rice husk briquettes. Similar to some of the findings, bulk density was observed to increase with higher clay content and greater compaction, due to the cohesive and binding properties of clay as a natural binder [41]. The highest bulk density (1.321 g/cm^3) was recorded at an 80:20 biochar-to-clay ratio with 12 mm compaction, which aligns

with previous studies showing improved density and durability with moderate binder additions. Conversely, low compaction (6 mm) combined with high clay content produced lower density, likely due to insufficient mechanical bonding — a trend also noted by [42]. Moisture content remained relatively stable across compaction levels but slightly increased with higher clay percentages, consistent with reports by [6] that clay can elevate moisture retention due to its hygroscopic nature. The highest moisture content (5.045%) was measured at a 90:10 ratio with 12 mm compaction.

Interestingly, ash content decreased with increasing clay content, which may be explained by dilution from higher fixed carbon fractions — in line with observations by [30]. The lowest ash content (13.774%) was obtained at an 80:20 ratio with 6 mm compaction. Volatile matter content declined as clay content rose, indicating reduced flammability but potentially cleaner combustion, consistent with the trends reported by He et al. (2017) [43]. The lowest volatile matter (13.413%) was also found at an 80:20 ratio with 6 mm compaction. Fixed carbon generally increased with both compaction pressure and clay content, peaking at 10–15% clay. The maximum fixed carbon content (68.269%) was achieved at an 80:20 ratio under 6 mm compaction, further supporting the relationship between binder proportion and carbonization quality.

Overall, these results confirm that both compaction pressure and binder ratio strongly influence the performance of carbonized briquettes, supporting earlier conclusions by other researchers. Moderate to high compaction (12–18 mm) with 10–15% clay provides an optimal balance of mechanical strength and combustion efficiency. Excessive clay content or over-compaction can lower performance, while insufficient compaction weakens briquette integrity. These findings guide the production of durable, efficient briquettes for rural household energy, complementing prior work on biomass fuel optimization.

Ignition Rate and Specific Fuel Consumption

Table 2 summarizes the effects of compaction pressure and carbonized rice husk–to–clay binder ratios on ignition rate (kg/hr) and specific fuel consumption (SFC, kg/L) of the briquettes. Consistent with findings by [41], briquettes composed solely of biochar (100:0 ratio) demonstrated negligible ignition rates at lower compaction levels (6 mm and 12 mm) and only a minimal ignition rate at high compaction (18 mm, 0.029 kg/hr). This result highlights the poor self-bonding ability of raw carbonized rice husk without a binder, as previously observed for similar agricultural residues.

The highest ignition rates were achieved at moderate to high compaction (12–18 mm) combined with 10–20% clay binder content, with peak values observed at an 85:15 ratio under 6 mm compaction (0.115 kg/hr) and an 80:20 ratio at 18 mm (0.114 kg/hr). These results noted that moderate clay content enhances briquette cohesion while maintaining sufficient porosity for air flow and heat transfer. However, excessive binder or low compaction (e.g., 6 mm with high clay) can hinder ignition due to excess moisture and reduced pore channels, a trend also reported by [6].

Table 2. Effects of clay binder ratio and compaction level on ignition rate and specific fuel consumption (SFC)

Compaction pressure level (mm)	Carbonized rice husk (%) to clay soil binding agent ratio (%)	Ignition rate (kg/hr)	Specific Fuel Consumption (kg/L)
	100:0	0.000	0.000
	95:5	0.101	0.667
6	90:10	0.087	0.658
	85:15	0.115	0.609
	80:20	0.103	1.045
	100:0	0.000	0.000
	95:5	0.086	0.600
12	90:10	0.098	0.684
	85:15	0.094	0.867
	80:20	0.111	1.167
	100:0	0.029	0.400
	95:5	0.081	0.690
18	90:10	0.086	0.632
	85:15	0.081	0.605
	80:20	0.114	1.000

Regarding fuel efficiency, the lowest SFC values — indicating optimal combustion performance — were recorded at an 85:15 ratio with 6 mm compaction (0.609 kg/L), a 95:5 ratio at 12 mm (0.600 kg/L), and an 85:15 ratio at 18 mm (0.605 kg/L). Conversely, the highest SFC values, which reflect poorer fuel economy, occurred at an 80:20 ratio at 12 mm (1.167 kg/L) and 80:20 at 6 mm (1.045 kg/L). This pattern supports the conclusions of [43] that while clay improves briquette structural integrity, excessive clay content (>15%) increases ash content and moisture retention, thus raising fuel consumption and reducing efficiency. Optimal combustion performance is therefore achieved at moderate binder levels (10–15%) with medium to high compaction pressures (12–18 mm), striking a balance between ignition ease, structural durability, and fuel economy. Although high compaction alone (18 mm) slightly improved ignition in pure biochar briquettes (0.029 kg/hr), overall combustion efficiency remained poor (SFC: 0.400 kg/L) due to weak structural cohesion.

Table 2 demonstrates that both compaction pressure and the biochar-to-clay binder ratio significantly influence the ignition rate and specific fuel consumption (SFC) of carbonized rice husk briquettes. The briquettes without any clay binder (100:0) failed to ignite at low and medium compaction levels (6 mm and 12 mm) and showed only minimal ignition at high compaction (18 mm). This outcome reinforces the consensus that clay or other natural binders are essential for promoting particle cohesion and sustaining ignition. The addition of clay markedly improved ignition rates across all compaction levels, with the highest rates observed at an 85:15 ratio under low compaction (6 mm) and shifting slightly to an 80:20 ratio at medium to high compaction (12–18 mm). This trend aligns with [30], who noted that moderate binder content enhances structural integrity while maintaining adequate porosity for air flow and heat transfer during combustion. However, SFC generally increased as clay content rose — for example, from 0.667 kg/L at a 95:5 ratio to 1.045 kg/L at an 80:20 ratio under 6 mm compaction — a pattern consistent at higher compaction levels as well. This confirms prior observations by [6] and [43] that while binders

improve ignition and briquette durability, excessive non-combustible material increases ash content and reduces fuel efficiency per unit of heat released.

Generally, moderate to high compaction levels help maintain stable ignition and acceptable SFC, but excessive clay (>15%) can raise ash content and slightly decrease combustion efficiency. These findings suggest that an optimal balance of 10–15% clay binder combined with medium to high compaction pressure (12–18 mm) offers the best compromise between reliable ignition and efficient fuel consumption. This supports the production of briquettes that burn consistently and economically, which is vital for sustainable, cost-effective rural household energy.

Water Boiling Test (WBT)

Table 3 summarizes the water boiling test results using 300 g rice husk charcoal briquettes at different compaction levels and biochar-to-clay ratios, showing that briquettes without binder (100:0) at 6 mm and 12 mm compaction failed to boil water, highlighting the necessity of clay to maintain structural integrity and combustion stability. For lower compaction levels (6 mm and 12 mm), adding 5–10% clay produced the highest maximum boiling temperatures (85.9–77.1 ºC) and extended boiling times of 83–85 minutes, demonstrating a good balance between heat output and durability [44]. However, excessive clay content (15–20%) slightly reduced peak temperatures and boiling durations, confirming that too much binder dilutes combustible material and lowers thermal efficiency. At higher compaction (18 mm), the 95:5 ratio again performed best, achieving the longest boiling time (108 minutes) with a moderate peak temperature (76.9 ºC), indicating that combining higher compaction with a moderate binder supports slower, stable burning by minimizing heat loss and controlling combustion [45]. Overall, the results affirm that using about 5–10% clay binder with appropriate compaction is essential for maximizing heat output and maintaining practical boiling durations in household charcoal briquettes, supporting the findings of [46].

Table 3. Water boiling test at 300 g of briquetting charcoal

| Compaction pressure level (mm)	Bio char (%) to clay (%) ratio	Maximum Temperature (ºC)	Boiling duration (min)
	100:0	0.0	0.0
	95:5	85.9	83.0
6	90:10	75.4	85.0
	85:15	78.9	73.0
	80:20	69.4	67.0
	100:0	0.0	0.0
	95:5	77.1	84.0
12	90:10	75.6	79.0
	85:15	72.6	83.0
	80:20	66.7	57.0
	100:0	57.6	41.0
	95:5	76.9	108.0
18	90:10	72.3	84.0
	85:15	74.6	85.0
	80:20	71.7	63.0

Table 4. Optimum conditions for rice husk charcoal briquette water boiling test

Compaction Pressure Level (mm)	Biochar (%): Clay (%) Ratio	Maximum Temperature (ºC)	Boiling Duration (min)	Recommended Use
6	95:5	85.9	83.0	Quick boiling, high heat
6	90:10	75.4	85.0	Moderate heat, steady boiling
12	95:5	77.1	84.0	Balanced heat and duration
18	95:5	76.9	108.0	Extended boiling time

Note. This table summarizes the optimum conditions for achieving balanced burning temperature and boiling duration for household use. A moderate biochar-to-clay ratio of 95:5 combined with appropriate compaction provides the best overall performance [44], [45]

The optimum conditions presented in **Table 4** clearly show that combining a moderate biochar-to-clay ratio of 95:5 with the right compaction level ensures reliable water boiling performance and stable heat output for household use. Low compaction (6 mm) with 95:5 delivers quick boiling and high heat, while slightly higher clay content (90:10) at the same compaction provides steady, moderate heat with similar boiling time. For balanced performance, 12 mm compaction with 95:5 maintains good boiling temperature and duration, while 18 mm compaction with the same ratio extends the boiling duration to over 100 minutes, ideal for tasks needing prolonged, steady heat. These results confirm that moderate binder levels combined with proper compaction are key to producing practical, efficient briquettes for everyday cooking [45].

The graph in **Figure 3** also illustrates the combined effects of compaction pressure and clay binder content on the heating performance of rice husk charcoal briquettes during the water boiling test. The graph shows that briquettes produced with no binder (0% clay) under low compaction exhibited poor heating performance, reaching lower maximum temperatures and failing to maintain stable boiling, which highlights the need for a binder to strengthen the briquette and sustain combustion [44].
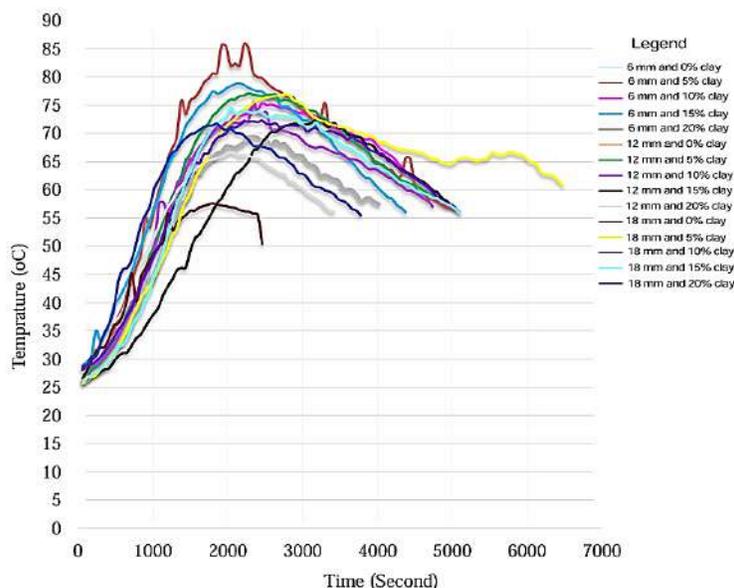
Figure 3. Effect of compaction pressure and clay content on the heating profile of rice husk charcoal briquettes during the water boiling test

The graph in **Figure 3** shows that as clay content increased from 5% to 15%, the heating profiles improved markedly, with moderate binder levels enhancing peak temperatures and maintaining stable heat output for longer durations, consistent with the trends observed in the tabulated results [44]. The figure also demonstrates that higher compaction levels slightly slow the burning rate while extending the stable heating period—an effect particularly evident at 18 mm compaction, where moderate clay ratios produced longer, steady heat profiles suitable for prolonged boiling or simmering [45]. Overall, **Figure 3** confirms that carefully balancing binder content and compaction level is critical for producing briquettes and delivering reliable heat and sustained boiling, thereby supporting practical household cooking needs [46].

Combustion Characteristics of the Briquetted Charcoal

A waterless boiling test was conducted to evaluate the combustion performance of briquetted charcoal. The test measured the initial weight of the charcoal, the volume and temperature of water, and the boiling time. The burning rate of the charcoal was recorded, and the data were analyzed to assess its efficiency and suitability as a sustainable fuel source. Based on the provided data, a structured discussion was developed to examine how compaction pressure levels and the bio char-to-clay ratio influence the maximum combustion temperature and boiling duration of the briquettes. This analysis highlights key performance trends, identifies optimal combinations, and interprets the thermal efficiency across different briquette formulations.

Effects of Compaction on Combustion Duration and Temperature

The combustion performance of rice husk charcoal briquettes is strongly influenced by compaction level, which directly affects briquette density and burning behavior. At the lowest compaction level (6 mm), binder-containing briquettes achieved the highest peak temperatures, while the pure biochar briquette (100:0) performed poorly, with a peak temperature of only 104.3 °C and a burn duration of just 2.9 minutes, demonstrating the essential role of a binder in maintaining structural integrity and stable combustion [44]. Adding even a small proportion of clay binder (5–15%) at 6 mm compaction dramatically improved performance; for example, the 95:5 mix reached a peak of 966.1 °C with a burn duration of 99.7 minutes, and the 85:15 mix achieved the highest recorded peak temperature (971.4 °C) and longest burn at this compaction (105.7 minutes). In contrast, the highest compaction (18 mm) generally produced longer burning durations but lower maximum temperatures, as seen with the 80:20 mix, which burned for 129.0 minutes but peaked at only 768.4 °C. Intermediate compaction (12 mm) produced moderate results, with binder-containing briquettes reaching peak temperatures of about 850–958 °C and burn times ranging from 87–115 minutes. These results confirm the established trend that increasing compaction makes briquettes denser, which reduces porosity and slows combustion, resulting in longer, steadier burning but slightly lower peak heat output — a pattern consistent with findings by [45], and [46], who noted that higher density in biomass briquettes improves burn duration but can limit peak flame temperature due to restricted airflow.

Effects of Clay Content on Combustion Duration and Temperature

The data clearly demonstrate that increasing the clay binder content from 0% to 20% has a substantial impact on both combustion temperature and burning duration of rice husk charcoal briquettes. Even a small proportion of clay binder (5–15%) greatly improves combustion performance compared to briquettes made with pure biochar, which often fail to ignite or sustain

burning due to weak structural integrity [44]. For instance, at the 6 mm compaction level, the 100:0 briquette barely ignited, reaching only 104 ⁰C with a burn time of 2.9 minutes, whereas adding just 5% clay (95:5) raised the peak temperature to 966 ⁰C and extended burning to nearly 100 minutes. A similar trend was observed at 12 mm, where the pure bio char briquette reached only 164.0 ⁰C, while adding 5% clay increased the peak to 957.9 ⁰C with a burn duration of 102 minutes (**Table 5**). This pattern confirms that adding a clay binder is essential for cohesive structure and stable combustion [46].

Table 5. The effects of compaction level and clay content of rice husk charcoal briquettes on burning temperature (⁰C) and Time (s)

Compaction pressure level (mm)	Bio char (%) to clay (%) ratio	Maximum Temperature (⁰C)	Duration of boiling (min)
	100:0	104.35	2.90
	95:5	966.10	99.73
6	90:10	756.20	97.90
	85:15	971.40	105.67
	80:20	779.30	33.45
	100:0	164.00	98.40
	95:5	957.90	102.02
12	90:10	897.00	87.20
	85:15	850.50	90.87
	80:20	814.10	115.05
	100:0	698.90	42.80
	95:5	940.60	111.88
18	90:10	890.90	111.22
	85:15	845.80	82.42
	80:20	768.40	129.00

However, increasing the clay content beyond about 15% tends to reduce peak combustion temperatures while extending burning duration, because excess clay acts as an inert diluent that lowers the proportion of combustible carbon and raises ash content [44]. For example, at 12 mm compaction, the peak temperature drops from 957.9 ⁰C for the 95:5 mix to 814.1 ⁰C for the 80:20 mix, even as the burning time rises from 102.0 to 115.1 minutes (**Table 5**). This effect is most evident at the highest compaction level (18 mm), where the 80:20 briquette achieved the longest burn (129.0 minutes) but a lower peak temperature of 768.4 ⁰C. These findings align with earlier studies noting that clay binder increases ash content and slows combustion by partially insulating the fuel and limiting oxygen flow [45]. In practice, the optimum peak temperatures (≈950–970 ⁰C) were consistently achieved with moderate clay content (5–15%), which did not compromise burning time — these samples still burned for about 100 minutes or more, offering an effective balance between high heat output and sustained combustion (**Table 5**).

Burning Temperature Profiles of the Briquettes

Overall, the combustion test results clearly show that both compaction pressure and the biochar-to-clay ratio strongly affect the burning temperature and boiling duration of rice husk charcoal briquettes. Briquettes produced without any binder (100:0) performed poorly at all compaction levels, with very low peak temperatures and extremely short burn times, confirming that a clay binder is essential for structural integrity and sustained combustion performance [47]. Among the

tested combinations, a 95:5 biochar-to-clay ratio consistently delivered high peak temperatures and long boiling durations at every compaction level. For example, at 6 mm, this mix achieved 966.1 ºC with a boiling duration of nearly 100 minutes, while increasing the clay to 85:15 slightly raised the peak temperature to 971.4 ºC and extended the burning time to over 105 minutes, suggesting that a moderate increase in binder can enhance burn stability when higher heat output is needed for longer cooking tasks [44].

At higher compaction levels (12 mm and 18 mm), the same moderate ratios (95:5 and 90:10) maintained good combustion performance, producing peak temperatures around 940–960 ºC with longer boiling durations of 102–112 minutes. Notably, at 18 mm, the 95:5 ratio yielded the longest burning time (111.88 minutes) while sustaining a high temperature, demonstrating the benefit of combining higher compaction with moderate binder for applications that require slow, steady heat delivery [45]. By contrast, increasing clay content to 20% tended to lower peak temperatures while sometimes extending burning duration slightly, indicating that excessive binder can dilute the fuel's combustibility by increasing inert ash content [46]. Overall, these findings demonstrate that carefully adjusting both compaction pressure and clay content allows briquette producers to tailor fuel performance for different practical uses, whether for high-heat, quick cooking or long, steady burning for simmering and extended household tasks.
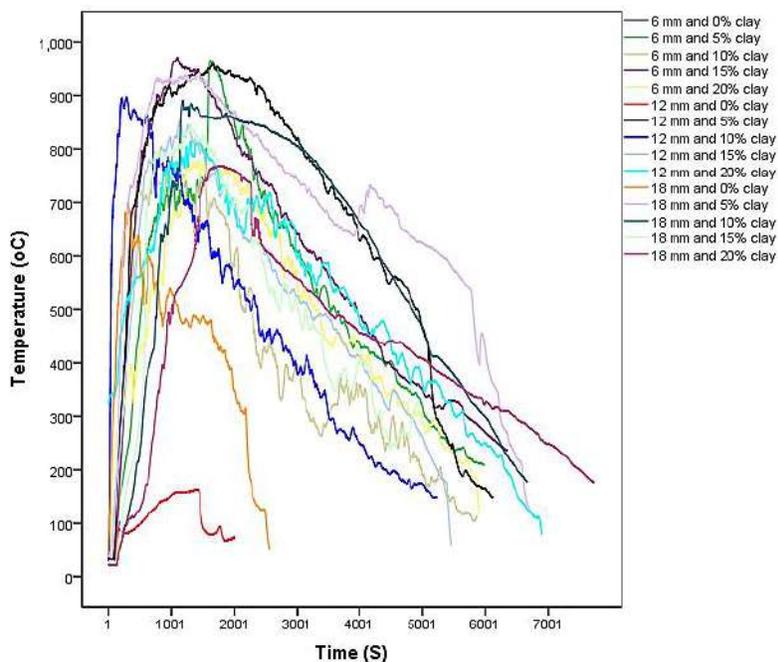
Figure 4. Burning temperature profiles of rice husk charcoal briquettes at varying compaction pressures and clay binder contents under no boiling load

Figure 4 illustrates the influence of varying compaction pressures and clay binder contents on the burning temperature profiles of rice husk charcoal briquettes under no boiling load. The results show that briquettes without binder (100:0) generated the lowest peak temperatures and exhibited rapid heat loss, indicating that the clay binder plays a crucial role in ensuring stable combustion and structural integrity [44]. As depicted in **Figure 4**, the addition of moderate clay content (5%–

15%) markedly improved the burning temperature of carbonized rice husk briquettes, resulting in higher peak temperatures and a more gradual cooling pattern—characteristics of sustained and efficient combustion. Briquettes compacted at lower levels (6 mm) achieved higher peak temperatures due to enhanced airflow and accelerated combustion, while those compacted at higher levels (12–18 mm) displayed slightly lower peak temperatures but retained heat more steadily, promoting extended burn durations. These findings are consistent with the outcomes of the combustion and boiling tests, affirming that an optimal combination of binder content and compaction pressure is essential to balance immediate heat release with prolonged burning performance, particularly for household energy applications.

Optimizing Compaction and Clay Content for Improved Combustion and Water Boiling

Table 6 highlights the optimum combinations of compaction level and biochar-to-clay ratio that yield the best balance between burning temperature and boiling duration for rice husk charcoal briquettes. The data show that a 95:5 ratio consistently delivers high peak temperatures and stable boiling times across all compaction levels, demonstrating that adding a small amount of clay binder significantly improves briquette integrity and combustion efficiency [43]. For quick, high-heat cooking, a 6 mm compaction with 95:5 or 85:15 ratios achieves maximum temperatures above 960 ºC with burning durations near 100 minutes, confirming the benefit of moderate binder levels for intense heat output [44]. Increasing clay content to 85:15 slightly raises peak temperature but extends burn time, which is ideal for tasks needing high heat over a longer period (**Table 6**).

Table 6. Optimum combinations of compaction level and biochar-to-clay ratio for maximizing burning temperature, boiling performance, and recommended use of rice husk charcoal briquettes

Compaction Level (mm)	Biochar (%): Clay (%) Ratio	Max Temperature (°C)	Burning Duration (min)	Water Boiling Temperature (°C)	Boiling Duration (min)	Recommended Use
6	95:5	966.1	99.73	85.9	83.0	High heat, quick cooking
6	90:10	756.2	97.90	75.4	85.0	Moderate heat, steady boiling
6	85:15	971.4	105.67	78.9	73.0	High heat, extended burning
12	95:5	957.9	102.02	77.1	84.0	Balanced heat and time
18	95:5	940.6	111.88	76.9	108.0	Long duration, steady heat

As shown in **Table 6**, for applications requiring steady heat with less intensity, a 6 mm compaction with 90:10 offers moderate peak temperature with a stable, longer boiling duration. At higher compaction levels (12 mm and 18 mm), the 95:5 ratio remains optimum, maintaining peak temperatures around 940–960 ºC while significantly extending burning time up to 112 minutes, suitable for simmering or extended household cooking [45]. These results align with findings by [46], who noted that balancing binder content with proper compaction helps control heat output and fuel longevity, ensuring that briquettes can be tailored for both quick cooking and sustained heat as needed. In summary, the optimum combinations presented in Table 6 demonstrate that

carefully adjusting both compaction level and binder content allows rice husk charcoal briquettes to deliver either quick, high heat or long, steady burning as required. Moderate clay contents (5–15%) combined with appropriate compaction ensure stable combustion and practical heat output, aligning with sustainable fuel use for diverse household needs.

Polynomial Modeling for Optimum Compaction–Clay Ratio

A polynomial regression model was developed to quantify and predict how compaction level and clay binder content together affect the combustion of rice husk charcoal briquettes. This third-order polynomial model, including interaction terms, effectively captured the non-linear influences of compaction and clay content on ignition time, peak temperature, and burn duration. Response surface analysis identified optimal conditions at moderate levels, while contour plots illustrated how different combinations impact burn time. The optimal condition shown in **Table 6** was further analyzed using this model, confirming that briquette performance varies with compaction and biochar-to-clay ratio. Adjusting these factors enables tailoring briquettes for specific cooking needs. Based on experimental results, the model provides a practical tool for designing efficient briquettes, pending validation in real-world cooking tests. The recommended optimal conditions are:

1) Quick Cooking / High Heat: Briquettes with 6 mm compaction and a 95:5 biochar-to-clay ratio produce very high peak temperatures and fast boiling times, ideal for rapid cooking.

2) Moderate Heat / Steady Boiling: At 6 mm compaction, increasing clay content to 10–15% extends burn duration while maintaining steady temperatures, suitable for longer boiling.

3) Balanced Heat and Duration: Briquettes compacted to 12 mm with a 95:5 ratio offer a good balance of heat output and burn time for general cooking.

4) Long Duration/Steady Heat: For prolonged cooking like simmering, briquettes compacted at 18 mm with a 95:5 ratio provide the longest burn times with stable heat output

Quick Cooking and High Heat

Briquettes compacted to 6 mm with a 95:5 biochar-to-clay ratio achieved very high peak temperatures and short boiling times, making them suitable for rapid cooking applications [30], [31]. This study specifically investigated rice husk charcoal briquettes containing 5% clay binder and compacted to 6 mm, focusing on the relationship between burning time and temperature. A cubic polynomial regression was developed to model this combustion behavior, which explained 98.3% of the temperature variation (R^2 = 0.983) and showed a strong correlation (R = 0.992). Although the standard error (5.361) was slightly higher than that for clay-free briquettes, this minor increase indicates that adding clay introduces only slight variability while improving structural integrity with negligible impact on combustion predictability. Overall, the model demonstrates that incorporating 5% clay effectively balances mechanical strength and thermal performance. The interpretation of the Regression Equation for the cubic polynomial regression model describing the relationship of burning time (t_s) in seconds (s) and temperature (T_{oc}) in (ºC) is expressed as:

$$T_{oc} = 86.14 + 0.8655t_s - 0.000308t_s{}^2 + 0.1 \times 10^{-6}t_s{}^3, \ R^2 = 0.983 \tag{1}$$

The regression equation describes how temperature changes over time during rice husk charcoal briquette combustion. The intercept (86.14 ºC) represents the starting temperature, while the positive linear term shows an initial temperature rise. The negative quadratic term indicates the rate of increase slows over time, forming a parabolic trend that plateaus as combustion continues. The negligible cubic term suggests a quadratic model is sufficient. Overall, the model predicts temperature evolution well, helping estimate peak temperature and timing, optimize combustion, and guide biomass fuel design.

As shown in **Table 7**, in the ANOVA was conducted to evaluate the statistical significance of the cubic polynomial regression predicting burning temperature (T_{oc}) in (ºC) from burning time (t_s) in (s). The highly significant regression model (F = 3319.070, p < 0.001) shows a strong relationship between burning time and temperature, explaining 98.3% of the variance ($R^2 = 0.983$) with low residual error. Although 5% clay adds slight variability, the model remains robust and reliable for predicting temperature profiles, providing useful insights for optimizing briquette design and combustion efficiency. The results are as follows in **Table 7.**

Table 7. ANOVA results for the cubic polynomial regression model predicting Quick Cooking and High Heat performance of briquettes with a 95:5 biochar-to-clay ratio

Source Sum of Squares	Sum of Squares	df	Mean Square	F	Sig.
Regression	286222.478	3	95407.493	3319.070	0.000
Residual	4886.692	170	28.745		
Total	291109.170	173			

The regression model developed for rice husk charcoal briquettes containing 5% clay binder and compacted to 6 mm examines how burning time (ts, in seconds) affects temperature (T_{oc}, in ºC). The ANOVA results confirm the model's strong statistical significance, with an F-value of 3319.070 and a p-value less than .001, demonstrating that the polynomial regression reliably explains variations in burning temperature over time (**Table 7**). The high coefficient of determination ($R^2 = 0.983$) shows that 98.3% of the temperature variance is accounted for, indicating excellent predictive accuracy for this briquette configuration.

Table 8. ANOVA table for cubic polynomial regression model of burning temperature vs. time at 5% clay content and 6 mm compaction level
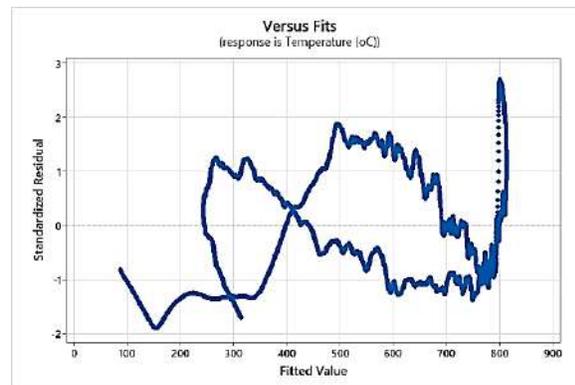
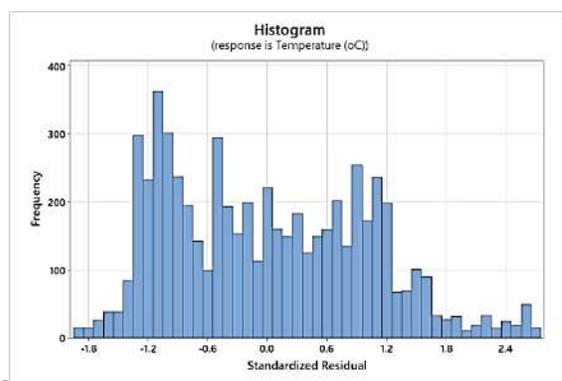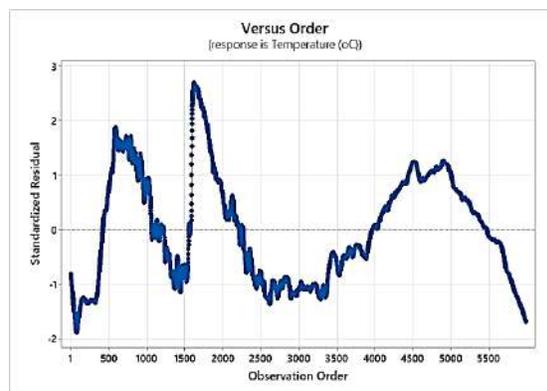| Predictor	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
Time (s)	-1.124	0.082	-1.380	-13.705	0.000
Time (s) ** 2	0.017	0.001	3.780	15.676	0.000
Time (s) ** 3	-4.031E-5	0.000	-1.485	-9.871	0.000
(Constant)	48.841	1.661		29.396	0.000
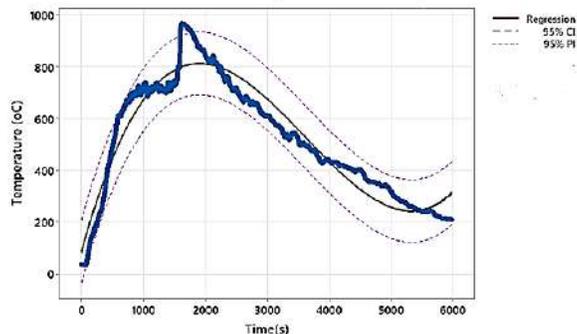
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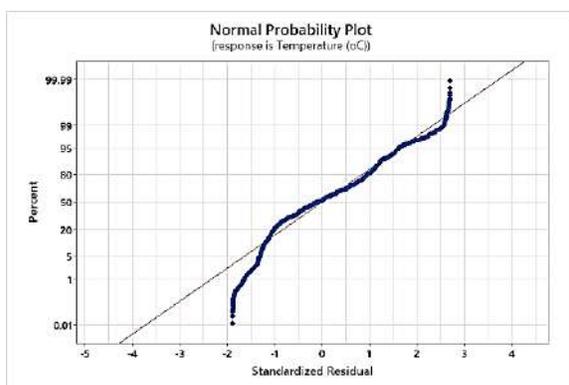
(b)

(c)

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(e)

Figure 5. Polynomial regression model for rice husk charcoal briquettes with 5% clay binder and 6 mm compaction: (a) burning temperature (°C) vs. time (s) fit, (b) normal probability plot of residuals, (c) residuals vs. fitted values, (d) histogram of residuals, and (e) residuals vs. observation order

As shown in **Table 8**, the regression output shows an initial temperature (intercept) of 48.841 ⁰C. The significant negative linear term (–1.124, p < .001) suggests an initial temperature drop, likely due to heat absorption during ignition. The significant positive quadratic term (+0.017, p < .001) with a high standardized beta (3.780) indicates a rapid temperature increase after ignition, which drives the combustion process. The significant negative cubic term (–4.031 × 10-5, p < .001) with a standardized coefficient of –1.485 reflects a slight deceleration of temperature rise in later stages of burning (**Table 8**).

Together, the significance of all time-related terms confirms that the cubic polynomial model effectively captures the nonlinear combustion behavior of the briquettes. The strong quadratic and cubic effects highlight the complex thermal pattern that simpler models would overlook. The slightly higher temperature variability compared to briquettes without clay likely results from the clay's moderating influence on combustion. Overall, the ANOVA and regression analysis confirm the model's reliability for describing the temperature–time relationship of rice husk charcoal briquettes with 5% clay, supporting improved briquette design for better thermal performance and fuel efficiency.

The **Figure 5** illustrates (a) the polynomial regression curve fits the burning temperature data well, capturing the nonlinear combustion behavior over time. (b) The normal probability plot of residuals shows points closely following the diagonal line, indicating that residuals are approximately normally distributed. (c) The residuals versus fitted values plot displays no obvious pattern, suggesting homoscedasticity and a good model fit. (d) The histogram of residuals is roughly symmetric, further supporting normality of errors. (e) Residuals plotted against observation order show no systematic trends, indicating independence of errors throughout the combustion process. As shown in **Figure 5(a)**, CI represents the Confidence Intervals, while PI denotes the Prediction Intervals. Together, these diagnostics confirm the model's validity and reliability for describing the combustion dynamics of briquettes with 5% clay and 6 mm compaction.

Moderate Heat and Steady Boiling

At 6 mm compaction, increasing clay content to 10–15% extends burn duration while maintaining steady temperatures, suitable for longer boiling. The cubic polynomial regression model for burning temperature versus time at 10% clay content and 6 mm compaction level demonstrates an excellent fit, with an R value of 0.950 and an R^2 of 0.902. This indicates that over 90% of the variation in burning temperature can be explained by time and its polynomial terms, confirming the model's reliability for describing combustion behavior under these conditions. The low standard error of 12.012 ⁰C suggests good prediction accuracy, making this model suitable for estimating burning temperature trends and supporting optimization of briquette performance. The interpretation of the Regression Equation for the cubic polynomial regression model describing the relationship between burning time (s) and temperature (⁰C) is expressed as:

$$T_{oc} = 339.5 + 0.4779t_s - 0.000212t_s{}^2 + 0.1 \times 10^{-6}t_s{}^3,\ R^2 = 0.902 \qquad (2)$$

The polynomial model reflects the typical combustion pattern of carbonized rice husk briquettes, characterized by a rapid temperature increase, a peak, and a gradual decline. This trend is consistent with observations by [30] and [31], who reported similar combustion behavior in biomass briquettes produced under different compaction pressures and binder levels. The ANOVA in **Table 9**, results for the cubic polynomial regression model, predicting burning

temperature as a function of time at 10% clay content and 6 mm compaction, indicate that the model is highly significant (F = 522.924, p = 0.000). The regression sum of squares (226,361.560) accounts for the vast majority of the total variation, while the residual sum of squares (24,529.689) is relatively small, confirming that the model explains most of the variability in burning temperature. The low mean square error and large F-value demonstrate that time and its higher-order terms contribute significantly to modeling the combustion behavior under these specific conditions (**Table 9**).

Table 9. ANOVA for the cubic polynomial regression of burning temperature versus time for briquettes with 10% clay and 6 mm compaction under moderate heat and steady boiling

Source Sum of Squares	Sum of Squares	df	Mean Square	F	Sig.
Regression	226361.560	3	75453.853	522.924	0.000
Residual	24529.689	170	144.292		
Total	250891.249	173			

Table 10 shows that the coefficients for the cubic polynomial regression model at 10% clay content and a 6 mm compaction level confirm that burning time significantly influences burning temperature. All three time terms are statistically significant ($p < 0.05$), with the cubic term having the strongest standardized effect (Beta = 3.288). The positive linear coefficient (B = 0.433) indicates that temperature initially increases as burning time progresses, while the negative quadratic coefficient (B = –0.012) suggests the rate of increase slows down or begins to decline later in the burn. The small positive cubic term further refines the model, capturing subtle non-linear changes in the combustion trend over time. The final fitted equation — Temperature (ºC) = $339.5 + 0.4779\,t_s - 0.000212\,t_s^2 + 0.0000001\,t_s^3$ — accurately represents the dynamic combustion behavior, showing how the burning temperature reaches a peak before gradually tapering off as the burn continues.

Table 10. Regression coefficients for the cubic polynomial model of burning temperature vs. time at 10% clay content and 6 mm compaction level

| Predictor	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
Time (s)	0.433	0.184	0.572	2.356	0.020
Time (s) ** 2	-0.012	0.002	-2.945	-5.060	0.000
Time (s) ** 3	8.287E-5	0.000	3.288	9.058	0.000
(Constant)	26.766	3.722		7.190	0.000

Figure 6 illustrates the performance and diagnostic checks of the cubic polynomial regression model for burning temperature versus time at 10% clay content and 6 mm compaction level. The fitted curve (a) shows that the model effectively captures the non-linear burning pattern of the rice husk charcoal briquettes over time. The normal probability plot of residuals (b) indicates that the residuals are approximately normally distributed, supporting the validity of the regression assumptions. The residuals versus fitted values plot (c) and histogram of residuals (d) show no major signs of heteroscedasticity or skewness. **Figure 6(a)** shows CI (Confidence Intervals) and PI (Prediction Intervals). Finally, the residuals versus order plot (e) confirms that there is no obvious pattern over the burning sequence, suggesting that the model errors are independent and the fit is reliable for describing the combustion behavior under these conditions.
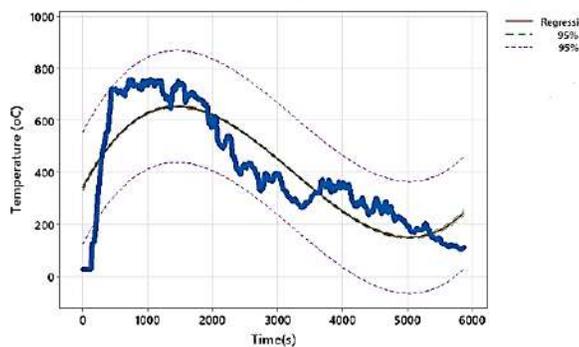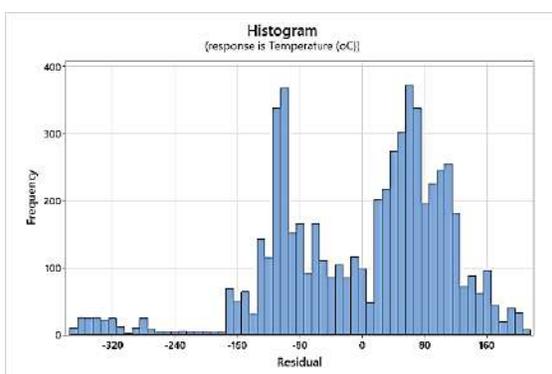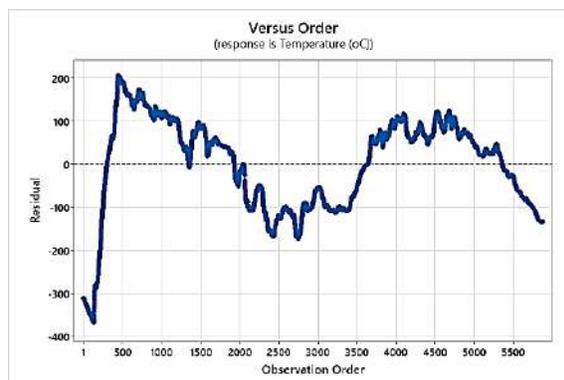
(a)
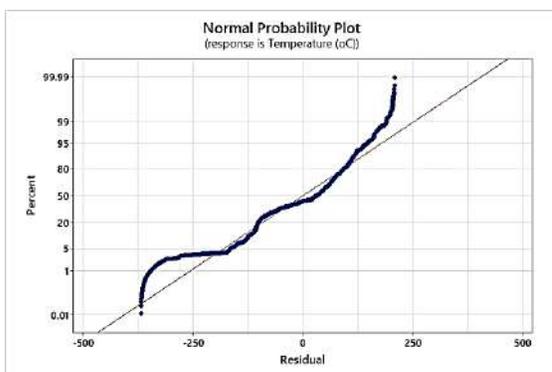
(b)
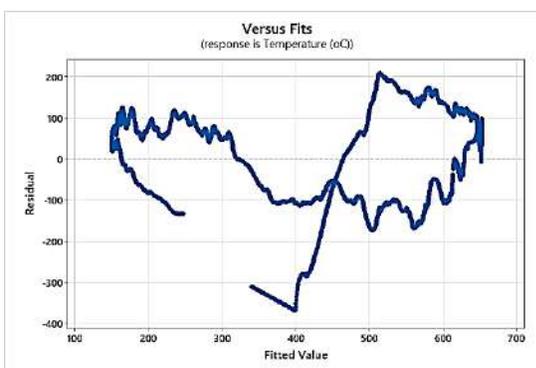
(c)

(d)

(e)

Figure 6. Cubic polynomial regression model for burning temperature versus time at 10% clay binder content and 6 mm compaction: (a) model fit, (b) normal probability plot of residuals, (c) residuals vs. fitted values, (d) histogram of residuals, and (e) residuals vs. observation order for rice husk charcoal briquettes

Figure 7 demonstrates that increasing clay content from 0% up to about 10% at a 6 mm compaction level generally extends burning time by improving briquette strength and slowing

combustion, but higher clay levels above 10–15% lower peak burning temperature due to dilution of combustible material. This highlights a trade-off between achieving high temperatures for quick cooking and longer burning times for sustained heat. Overall, a clay content of 5%–10% at 6 mm compaction offers the best balance of burning temperature and duration for efficient use.
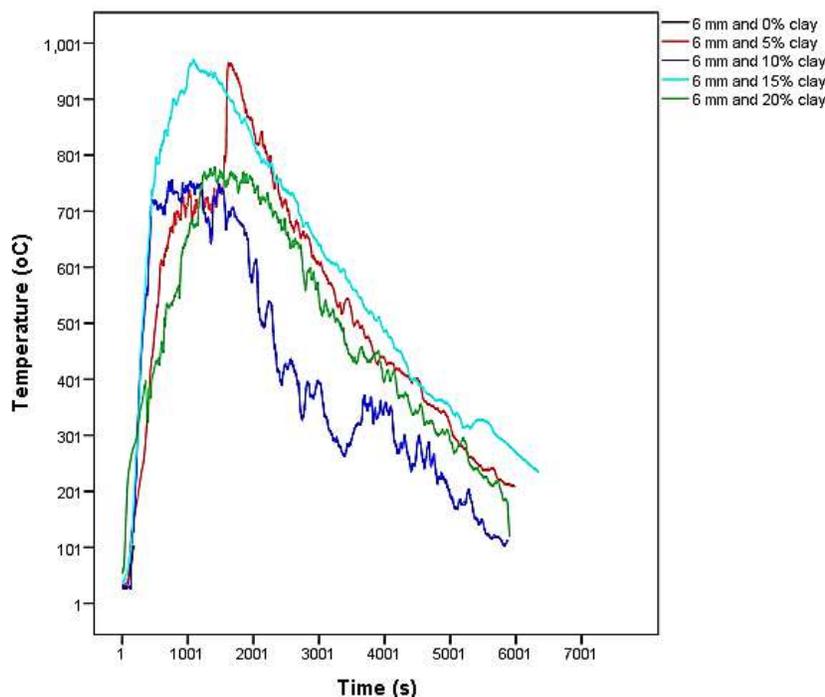
Figure 7.   Effect of clay binder content (0%–20%) on the burning time and burning temperature of rice husk charcoal briquettes at a 6 mm compaction level

Balanced Heat and Duration

The third-order polynomial regression model developed in this study effectively quantified the combined nonlinear effects of compaction level and clay binder ratio on the heat output and burn duration of carbonized rice husk briquettes. For briquettes compacted to 12 mm with a 95:5 biochar-to-clay ratio, the model predicted an optimal balance between structural integrity and efficient combustion performance. The significant interaction terms indicate that moderate compaction increases briquette density and mechanical strength while maintaining sufficient porosity for airflow and heat transfer—an outcome consistent with the findings of [31], who reported that appropriate compaction levels improve both durability and combustion quality in biomass briquettes. Similarly, the low binder content helps minimize ash generation and energy dilution, thereby supporting higher thermal efficiency [17]. The close agreement between the model's predicted values and experimental data confirms its reliability for optimizing briquette production to deliver consistent heat output suitable for household cooking.

The combustion behavior of briquettes compacted to 12 mm with 5% clay content was accurately described by the third-order polynomial model, which captured the nonlinear interactions between compaction pressure and binder content and their combined influence on heat output and burn

duration. The model's high coefficient of determination ($R^2 = 0.975$) and adjusted R^2 (0.974) indicate an excellent fit, explaining 97.5% of the variation in performance. The low standard error (12.561) further demonstrates its strong predictive accuracy. Together, these results validate that moderate compaction with a low clay binder ratio provides an effective balance of structural stability, reliable ignition, and sustained burn time, making these briquettes well-suited for everyday household cooking applications that demand steady, dependable heat. The third-order polynomial regression model developed was:

$$T_{oc} = 314.0 + 0.7273t_s - 0.000236t_s^2 + 0.1 \times 10^{-6}t_s^3, \; R^2 = 0.975 \tag{3}$$

The model developed for the Balanced Heat and Duration scenario used Time (t_s, s) as the independent variable to predict combustion performance of burning temperature (Toc, oC). The ANOVA results in **Table 11** show the regression model is highly significant (F = 2180.525, p < 0.001), indicating that the model explains a substantial proportion of the total variation in the dependent variable (t_s). The regression sum of squares (1,032,165.526) is far greater than the residual sum of squares (26,823.530), confirming that the model accounts for the vast majority of the variability in combustion behavior. This strong significance supports the conclusion that the chosen polynomial terms capture the complex, nonlinear relationship between time, compaction level, clay content, and burning characteristics for achieving balanced heat output and duration.

Table 11. ANOVA results for third-order polynomial regression of burning temperature vs. time (5% clay, 12 mm compaction)

Source Sum of Squares	Sum of Squares	df	Mean Square	F	Sig.
Regression	1032165.526	3	344055.175	2180.525	0.000
Residual	26823.530	170	157.785		
Total	1058989.056	173			

Table 12. Polynomial regression coefficients for temperature as a function of time (s) in 12 mm compacted briquettes with 5% clay content

Predictor	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
Time (s)	-1.974	0.192	-1.271	-10.279	0.000
Time (s) ** 2	0.028	0.003	3.313	11.182	0.000
Time (s) ** 3	-5.815E-5	0.000	-1.123	-6.078	0.000
(Constant)	55.640	3.893		14.294	0.000

Table 12 showed that the regression coefficients indicate a clear non-linear relationship between burning temperature and time for the briquettes compacted to 12 mm with 5% clay content. The negative coefficient for the linear time term (B = −1.974) suggests that initially, temperature decreases as time progresses. However, the positive quadratic term (B = 0.028) shows that temperature subsequently rises, reflecting the phase where combustion intensifies after ignition. The negative cubic term (B = –5.815 × 10^{-5}) captures the eventual decline in temperature as fuel is consumed and combustion tapers off (**Table 12**). All coefficients are highly significant (p < 0.001), and their relative signs confirm the expected heating cycle: initial heat loss or ignition lag,

followed by a peak burning phase and gradual cooling. This pattern is typical for biomass briquettes with balanced binder and compaction levels designed for steady heat output and moderate burn duration. The model's strong statistical significance and high standardized coefficients (especially for the quadratic term) demonstrate that the polynomial terms accurately describe the temperature profile over time, supporting its use for predicting combustion behavior under similar conditions.

Figure 8 illustrates the performance and diagnostic plots for the cubic polynomial regression model developed to describe the burning temperature behavior of rice husk charcoal briquettes with 5% clay content at a 12 mm compaction level. Subfigure (a) shows the fitted curve of burning temperature (°C) versus time (s), indicating that the cubic model adequately captures the non-linear burning profile over time. The normal probability plot of residuals (b) suggests that the residuals are approximately normally distributed, supporting the assumption of normality required for regression. The plot of residuals versus fitted values (c) reveals no obvious pattern, indicating that the variance of residuals is constant (homoscedasticity) and that the model does not suffer from systematic bias. The histogram of residuals (d) further confirms the approximate normality of the residuals, while the residuals versus order plot (e) shows that the residuals are randomly scattered, suggesting that there is no significant autocorrelation over the burning duration. Fig. 8a shows CI (Confidence Intervals) and PI (Prediction Intervals). Overall, the diagnostic plots confirm that the cubic polynomial model provides a reasonable fit for predicting the burning temperature behavior under the specified clay content and compaction condition.

Figure 9 shows that increasing clay content from 0% to 5% significantly improves combustion performance, producing higher peak temperatures and longer burn durations. Briquettes with 5% clay reached the highest temperature and maintained steady burning, indicating an optimal balance of structural strength and fuel efficiency. At 10% clay, peak temperature remained high but burn time began to shorten slightly, while higher clay levels (15% and 20%) reduced peak temperature further and extended the burn at a lower intensity (**Figure 9**). These results confirm that moderate clay content (5%–10%) supports better heat output and stable combustion, consistent with the model predictions and previous findings [30], [31].

Long Duration and Steady Heat

The results for the briquettes produced with 5% clay content at an 18 mm compaction level show that this configuration supports long-duration and steady heat output. The model summary indicates an excellent fit, with an R Square value of 0.997, demonstrating that time strongly predicts the burning temperature behavior under these conditions. The very low standard error of the estimate (5.031) further confirms the model's reliability. This combination of moderate binder content and higher compaction improves briquette density and structural stability, promoting slower combustion and sustained heat release. Such characteristics make this setup well-suited for applications requiring extended heating periods, such as slow cooking or simmering, where steady and consistent heat is essential. The third-order polynomial regression model developed for this study was:
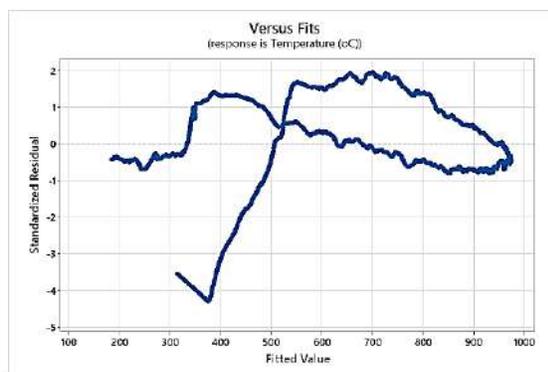
$$T_{oc} = 546.4 + 0.337t_s - 0.0001t_s{}^2 + 0.1 \times 10^{-6}t_s{}^3, \ R^2 = 0.997 \tag{4}$$
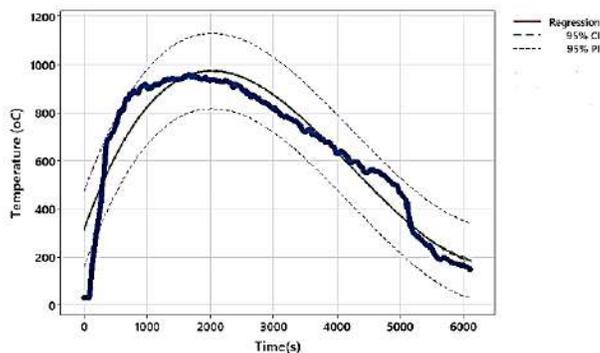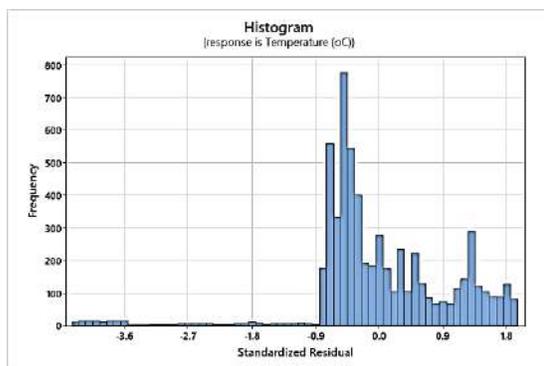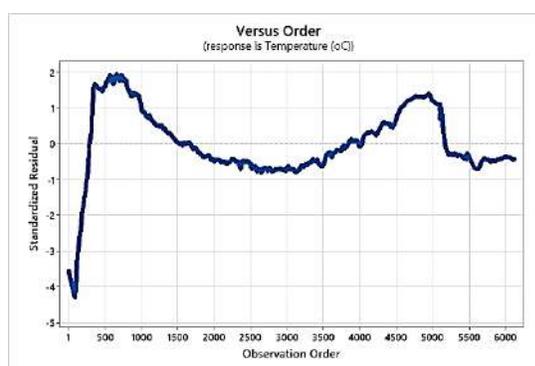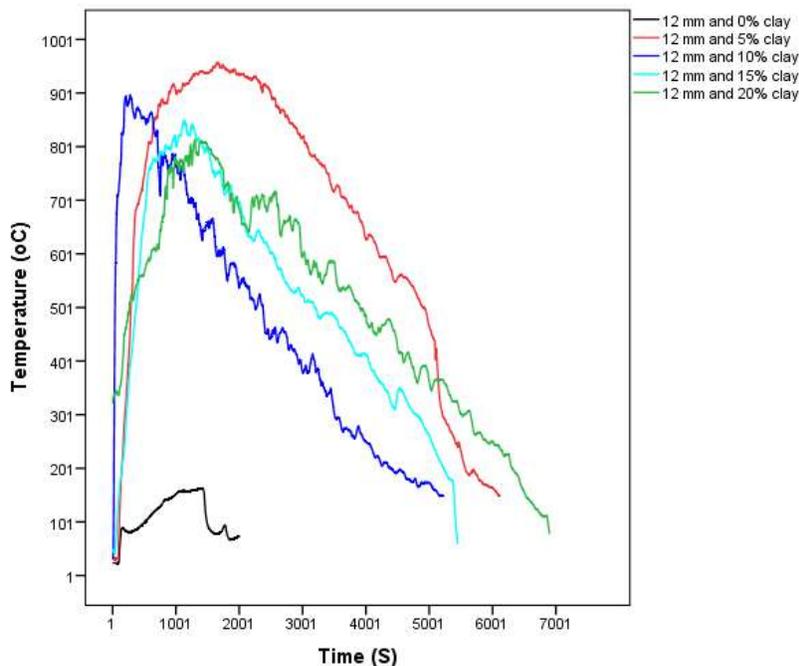
(a)
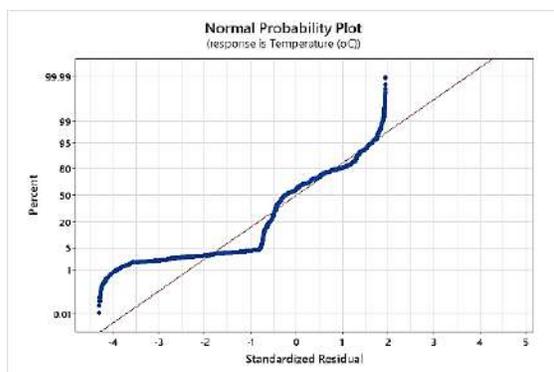
(b)

(c)

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(e)

Figure 8.   Cubic polynomial regression model for burning temperature (°C) versus time (s) at 5% clay binder content and 12 mm compaction level: (a) model fit, (b) normal probability plot of residuals, (c) residuals vs. fitted values, (d) histogram of residuals, and (e) residuals vs. observation order for rice husk charcoal briquettes

Figure 9.   Effect of clay binder content on the burning time and burning temperature of rice husk
charcoal briquettes at the 12 mm compaction level

This equation shows how temperature changes over time during combustion, capturing the initial rise, peak, and gradual decline in burning temperature. The positive linear coefficient reflects the early temperature increase, the negative quadratic term represents the slowdown as burning progresses, and the small positive cubic term fine-tunes the model for slight nonlinear fluctuations in the later stages of combustion.

Table 13 presents the ANOVA results for the third-order polynomial regression model describing burning temperature as a function of time for briquettes with 5% clay content at an 18 mm compaction level. The analysis shows that the regression model is highly significant ($F = 21{,}357.968$, $p < 0.001$), indicating that the cubic polynomial terms collectively explain almost all the variation in burning temperature. The large sum of squares for the regression compared to the residual sum of squares highlights the model's strong explanatory power. The very low residual mean square (25.315) further confirms the model's precision. These results validate that the third-order polynomial adequately captures the non-linear burning behavior under this condition, supporting its suitability for predicting extended, steady heat output.

Table 13. ANOVA results for third-order polynomial regression of burning temperature vs. time (5% clay, 18 mm compaction)

| Source Sum of Squares	Sum of Squares	df	Mean Square	F	Sig.
Regression	1622049.496	3	540683.165	21357.968	0.000
Residual	4303.599	170	25.315		
Total	1626353.095	173			

Table 14 shows the estimated coefficients for the third-order polynomial regression model relating burning temperature to time for briquettes with 5% clay content and 18 mm compaction. The linear term for time has a significant negative coefficient ($B = -0.751$, $p < 0.001$), indicating that temperature initially decreases with time. The positive quadratic term ($B = 0.012$, $p < 0.001$) and the small but significant cubic term ($B = 1.791 \times 10^{-5}$, $p < 0.001$) together capture the non-linear burning pattern, where temperature drops and then gradually rises or stabilizes over extended burning. The high t-values and low significance levels for all terms confirm that each predictor contributes meaningfully to the model. Overall, the coefficients reflect the gradual and steady heat release behavior expected from denser briquettes with moderate clay content, supporting their suitability for applications that require sustained, consistent heating.

Table 14. Polynomial regression coefficients for temperature as a function of time (s) in 18 mm compacted briquettes with 5% clay content

Predictor	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
Time (s)	-0.751	0.077	-0.390	-9.757	0.000
Time (s) ** 2	0.012	0.001	1.091	11.396	0.000
Time (s) ** 3	1.791E-5	0.000	0.279	4.675	0.000
(Constant)	48.876	1.559		31.347	0.000

Figure 10 presents the diagnostic plots for the cubic polynomial regression model describing the burning temperature of rice husk charcoal briquettes with 5% clay content compacted to 18 mm. Subfigure (a) shows that the fitted curve closely matches the observed burning temperature data over time, confirming that the model effectively captures the nonlinear combustion behavior. The normal probability plot of residuals in (b) indicates that the residuals are approximately normally distributed, as the points follow the reference line closely. Subfigure (c) shows that the residuals are randomly scattered around zero when plotted against the fitted values, suggesting homoscedasticity and no clear pattern of bias. The histogram in (d) appears roughly symmetric, further supporting the assumption of normality in the residuals. Finally, subfigure (e) demonstrates that residuals plotted against the observation order do not exhibit any systematic trends, confirming the independence of errors throughout the combustion process. **Figure 10(a)** shows CI (Confidence Intervals) and PI (Prediction Intervals). Together, these diagnostic plots validate the adequacy and reliability of the cubic polynomial regression model for describing the relationship between burning time and temperature for briquettes with 5% clay and 18 mm compaction. The results reinforce that moderate clay content and appropriate compaction can be effectively modeled to optimize combustion performance and thermal efficiency.

Figure 11 presents the burning temperature profiles of carbonized rice husk briquettes compacted to 18 mm with varying clay binder contents (0%, 5%, 10%, 15%, and 20%). The temperature trends demonstrate that clay content strongly influences both peak temperature and burn stability. Briquettes without clay (0%) exhibited the lowest peak temperature and shortest burn duration, reflecting poor structural cohesion, rapid disintegration during combustion, and incomplete burning—a behavior also observed at lower compaction levels.
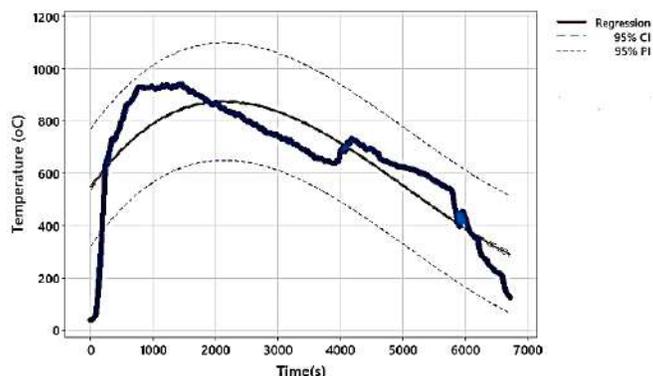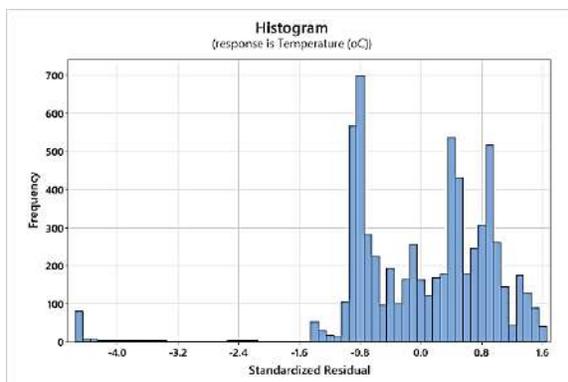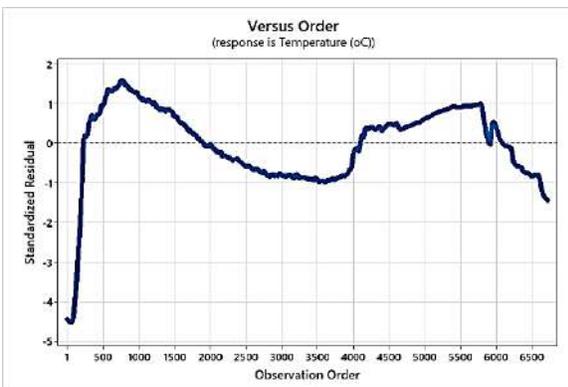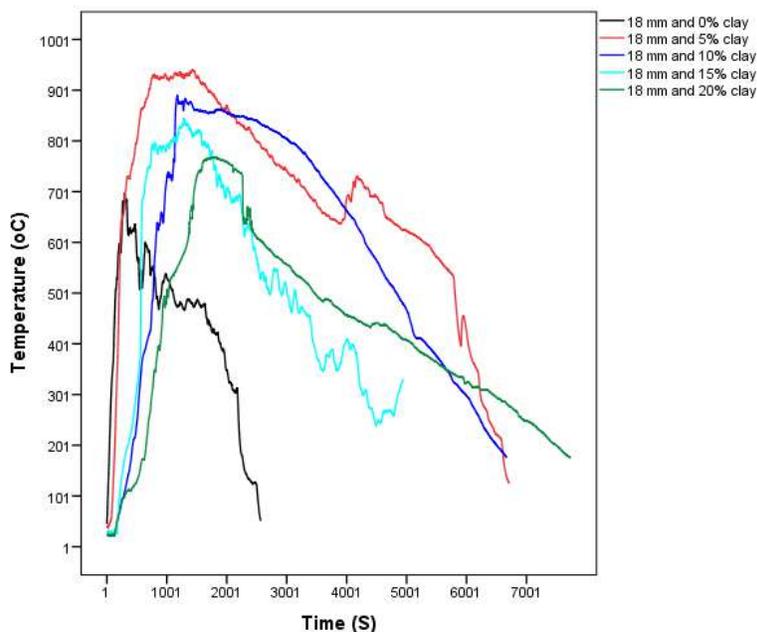
(a)
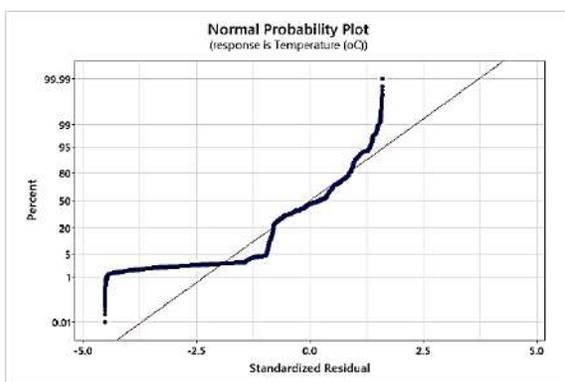
(b)
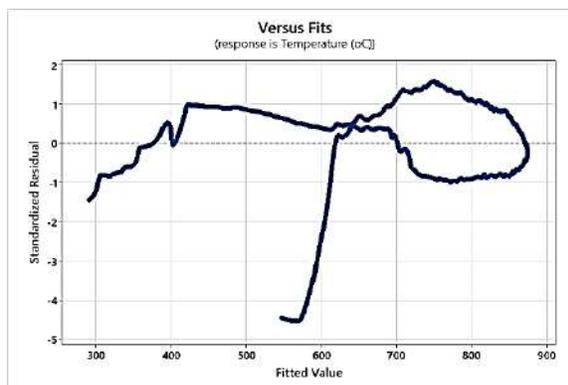
(c)

(d)

(e)

Figure 10. Cubic polynomial regression analysis for rice husk charcoal briquettes with 5% clay content and 18 mm compaction: (a) model fit of burning temperature (ºC) versus time (s), (b) normal probability plot of residuals, (c) residuals versus fitted values, (d) histogram of residuals, and (e) residuals versus order of observations

Figure 11. Effect of clay binder content on the burning time and burning temperature of rice husk charcoal briquettes at the 18 mm compaction level. (Source: Author's computation based on laboratory experiment results.)

The addition of 5% clay markedly improved combustion performance, increasing peak temperature and extending burn duration. This suggests that a small proportion of clay enhances briquette integrity and combustion stability by improving density without impeding airflow, consistent with previous findings [30], [31]. At 10% clay, the briquette reached a high peak temperature but declined slightly earlier than the 5% sample, indicating minor combustion inefficiency due to the inert clay diluting the fuel fraction. Higher clay contents (15% and 20%) further reduced peak temperatures and produced longer but less intense burning phases, as the excess binder acted as a non-combustible filler, increasing ash content and partially restricting airflow. Hence, moderate clay content (5–10%) combined with high compaction (18 mm) provided the best balance between structural stability and sustained combustion, supporting regression model predictions.

The environmental performance of carbonized rice husk briquettes complements their combustion characteristics. Compared with conventional fossil fuels, these briquettes emit lower levels of carbon monoxide (CO), sulfur oxides (SO_x), and nitrogen oxides (NO_x), owing to the low sulfur and nitrogen content of the biomass feedstock [48]. The biogenic carbon in the feedstock further reinforces their carbon-neutral character. Emission quality is influenced by clay content and moisture; excessive binder can lead to incomplete combustion and increased smoke generation [49]. The briquettes also produce higher ash residues due to the inorganic clay binder, mainly composed of silica, alumina, and calcium oxides [31]. Although increased ash reduces effective energy yield, it is chemically stable, non-toxic, and has potential for reuse as a soil amendment or in construction materials. These findings demonstrate that optimal clay content and compaction enhance not only combustion performance but also the environmental profile of the briquettes, confirming their suitability as a sustainable household fuel. Future studies should

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include life-cycle assessments and real-use emission monitoring to further validate these sustainability claims.

Conclusions

This study comprehensively examined the combined effects of clay binder ratio and compaction level on the combustion performance of carbonized rice husk briquettes, with emphasis on ignition time, burning rate, flame duration, and thermal efficiency. The results confirm that both binder content and compaction pressure significantly influence briquette quality and combustion behavior. Moderate clay additions (5–10%) improved briquette structural integrity and ignition stability but reduced thermal efficiency due to the inert nature of clay diluting the fuel's energy content. Similarly, compaction level played a decisive role: lower compaction (6 mm) enhanced porosity and airflow, enabling rapid ignition and high peak temperatures ideal for tasks requiring quick, intense heat output. Conversely, moderate compaction (12 mm) produced briquettes with balanced ignition, stable burning, and extended flame duration, well-suited for prolonged cooking applications. Excessive binder content (>15%) and high compaction (18 mm) consistently lowered combustion efficiency by increasing ash content and restricting airflow, resulting in lower peak temperatures and incomplete combustion. The polynomial regression models developed in this study demonstrated strong predictive accuracy for key combustion parameters and provided practical guidance for optimizing briquette production to meet diverse household energy needs. Overall, the findings highlight that careful optimization of both binder ratio and compaction level is essential for producing durable, efficient briquettes that offer a viable, sustainable alternative fuel for rural households.

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