Journal of Energy and Natural Resources
2025, Vol. 14, No. 2, pp. 54-68
https://doi.org/10.11648/j.jenr.20251402.14

Research Article

Evaluation and Modeling the Effect of Clay Soil Binding Ratio and Compaction Pressure Level on the Thermal Properties of Carbonized Rice Husk Briquetting Charcoal

Mersha Alebachew Fetene*, Dessye Belay Tikuneh

Department of Agricultural Engineering Research, Ethiopian Institute of Agricultural Research, Fogera National Rice Research, and Training Center, Bahir Dar, Ethiopia

Abstract

In developing countries, the mismanagement of agricultural residues such as rice husks not only exacerbates environmental pollution but also poses serious health risks. As a byproduct of the rice milling process, rice husks are abundant and largely underutilized, presenting a significant opportunity for renewable energy generation. This study evaluates and models the thermal properties of carbonized rice husk charcoal briquettes by analyzing the effects of varying clay soil binder ratios at five levels (0%, 5%, 10%, 15%, and 20%) and applied compaction pressures at three levels (6mm, 12mm, and 18mm) on burning temperature and duration. It involves a total of 15 treatments arranged using a 5×3 factorial experiment in a completely randomized design, with three replications for each treatment. The regression polynomial equation and modeling graph were developed to predict the outcomes of each treatment combination, enabling the identification of the optimal burning temperature and duration based on experimental findings and the modeling equation. The results showed that the treatment combination of 0% clay soil binder with a 6mm compaction pressure level resulted in a burning temperature below 110 ℃, with the low burning temperature lasting less than 5 minutes, the peak burning temperature of above 965 ℃ was achieved with 12 mm compaction pressure and a 5% clay soil binder ratio, while the longest burning duration, exceeding two hours, occurred with 18 mm compaction pressure and a 20% clay soil binder ratio. In general a lower clay soil binder ratio reduces ash content, increasing burning temperature, while medium compaction pressure optimizes airflow for peak combustion. Future research could explore alternative binders, compaction pressures, agricultural residues, moisture levels, and particle sizes to enhance burning temperature and duration.

Keywords

Carbonized Rice Husk, Binding Clay Soil, Compaction Pressure, Modeling, Burning Temperature, Burning Duration

1. Introduction

In developing countries, the improper management of agricultural residues poses serious challenges, including environmental pollution and health risks. Accumulated residues, often burned in open areas or dumpsites, release harmful toxins into the air and contaminate soil and water sources [12, 25, 15].

The rice milling process involves removing the husk from rice grains to produce polished white rice. The husk, which

*Corresponding author: mershalebachew@gmail.com (Mersha Alebachew Fetene)

Received: 11 April 2025; **Accepted:** 24 April 2025; **Published:** 29 May 2025

constitutes the outer layer of the rice grain, is separated during milling and often utilized as a byproduct, accounting for approximately 22% of the total grain proportion. Although typically regarded as waste, rice husk contains around 75% organic volatile compounds, making it a valuable resource for various applications [24, 14]. Organic rice husks and their varied compositions offer a promising renewable energy source, ideal for heat generation or biofuel production [20]. The burning of husk can generate a substantial amount of energy, offering an eco-friendly substitute for fossil fuels [24]. Nevertheless, untreated rice husks pose challenges due to their bulkiness, irregular shape, high moisture content, and low energy density, which hinder efficient handling, storage, transportation, and utilization [4].

Rice husks undergo carbonization to create carbonized rice husk, a more stable, energy-dense material with enhanced properties such as increased carbon content, making it a valuable fuel source for energy generation [26]. Rice husk is widely used to produce solid fuel variants such as pellets, briquettes, and loose forms. After burning, it leads to the formation of carbonized rice husk and residual rice husk biochar [13].

Briquettes, which are compressed blocks of coal dust or flammable biomass materials, represent a significant renewable energy solution aimed at mitigating deforestation and the excessive reliance on wood fuel. By providing a justifiable and cost-efficient alternative, briquettes play a crucial role in reducing the strain on forest ecosystems, fostering environmental preservation, and advancing clean energy practices. Their widespread adoption could serve as an essential step toward viable development and climate resilience [21, 29].

The briquetting process for carbonized rice husk is influenced by several critical factors. These include the moisture content, particle size, and presence of impurities in the rice husk, as well as the type, quality, and rice husk-to-binder ratio of the binder. Other key parameters include compression pressure, carbonization temperature and duration, compaction method, drying technique, and the specifications of the briquetting equipment. Furthermore, operational considerations such as operator expertise, storage conditions, transportation logistics, and market demand significantly affect the quality and feasibility of the briquettes [22, 17].

The selection and quality of the binder utilized in rice husk briquetting are paramount, as binders function as cohesive agents that significantly enhance the structural integrity, mechanical durability, and overall performance characteristics of the briquettes [5]. A suitable binder for rice husk briquetting must be affordable, widely available, and capable of maintaining the combustion properties of the solid fuel. It should also not compete with the human food supply. Due to its adhesive characteristics, clay soil serves as an excellent natural binder, enhancing the longevity and resilience of the briquettes. This economical and maintainable approach significantly improves the briquettes' quality, making them ideal for use as cooking fuel and in energy generation [9].

Compaction pressure denotes the force exerted to consolidate the mixture of rice husk and binder into high-density, solid briquettes during the briquetting process. Achieving the optimal compaction pressure is pivotal for fabricating robust, mechanically stable briquettes that resist structural failure. Excessive compaction pressure may induce over-compaction, thereby impairing ignition properties, while inadequate pressure can yield brittle or poorly bonded briquettes prone to disintegration [30].

Consequently, this study aims to explore the thermal properties of carbonized rice husk briquette charcoal by systematically evaluate the effects of varying clay soil binder concentrations (0%, 5%, 10%, 15%, and 20%) and compaction pressures (6 mm, 12 mm, and 18 mm). Key parameters, including burning temperature and combustion duration, are meticulously analyzed. A prominent aspect of this study lies in the development of regression models, articulated through both mathematical equations and graphical representations, to comprehensively elucidate the dynamic interdependencies among these factors, offering profound insights into their influence on carbonized rice husk briquette charcoal performance.

2. Material and Method

The study was conducted over a three-year period, from 2021 to 2023, at the Fogera National Rice Research and Training Center, located in Wereta, Ethiopia. The research activities took place within the workshop of the Agricultural Engineering Research Department. The center is geographically situated at latitude of 11°58' N and a longitude of 37° 41' E, with an elevation of 1810 meters above sea level.

2.1. Description of Research Materials

Carbonized rice husk briquetting is a viable and innovative technology that repurposes agricultural waste, specifically rice husks, as a renewable energy source. Through carbonization, rice husks are transformed into environmentally friendly charcoal alternatives, contributing to minimizing reliance on traditional wood-based charcoal. The process incorporates several essential components, including a carbonizer, hammer miller, mold maker, and cooking stove.

Carbonizer is designed to burn rice husks and produce biochar through controlled airflow. It features a pyramid shape with a square base, measuring 56 cm in length and 25 cm in height. The pyramid includes a 1 cm hole for airflow management, while a 100 cm-long tube with a 10 cm diameter serves as the air intake system to regulate oxygen supply during the carbonization process.

Hammer mill is designed to crush carbonized biochar into fine powder. The biochar is manually fed through the feed hopper, which serves as the entry point. A bottom screen regulates the particle size, ensuring uniformity. The discharge chute then directs the processed powder into a collection container, as illustrated in Figure 1 below.

Figure 1. Hammer Miller and Mold Maker.

Mold maker is shown in Figure 1, consists of a hydraulic jack, a sturdy frame, and a prism-shaped piston designed to compress the fermented mixture into briquette charcoal. The piston measures 3.5 cm square at the base and 10 cm in height, effectively molding the briquettes within the container. The mold maker utilizes 36 cubes as molds to produce uniform charcoal briquettes.

Cooking stoves are optimized to utilize charcoal briquettes produced from rice husks, offering a bearable cooking fuel source. Specifically designed for burning the briquettes effectively, these stoves provide a clean and efficient heat source for cooking.

The laboratory research materials and instruments utilized for testing the carbonized rice husk briquette process included rice husks for charcoal production and clay soil as a binding agent. Essential equipment comprised a precision balance for accurate weighing, a plastic bucket for mixing, and a spade for blending the materials. Further tools included a construction spoon for shaping, an oven for drying the briquettes mold, and a K-type thermocouple for precise temperature measurement during the process.

2.2. Procedure of the Experiments

Rice husks were sourced from the Agricultural Engineering Research rice milling workshop at the Fogera National Rice Research and Training Center. After collection, the husks were sun-dried to achieve the required average moisture content. Using a carbonizer, the rice husks were burned under controlled airflow to produce biochar. The resulting biochar was then ground into a fine powder with a carbonized rice husk hammer miller machine and stored in a plastic container for a week to ensure uniformity. The binding agent, clay soil, was subsequently mixed with the carbonized rice husk powder in varying proportions to prepare the briquetting mixture. The mixture was prepared by combining 2 kg of milled carbonized rice husk and clay soil with 2 liters of water, ensuring thorough mixing for uniform consolidation. Following a 24-hour fermentation period, the blended biochar and clay soil were transferred into a prism-shaped mold maker. Using a hydraulic jack press, the mixture was compressed at levels ranging from 6 mm to 18 mm, forming charcoal briquettes. The hydraulic jack was operated by alternately lowering and lifting it, allowing the biochar and clay binder to compress while water drained over three to five minutes. The briquettes were subsequently moisturized and placed on a leveled, compacted chip wood surface for drying until the required moisture content was achieved. Once dried, the briquettes, weighing 300 grams each, were burned using a cooking stove. The output burning temperature was then recorded with a K-type thermocouple to evaluate performance.

Figure 2. Procedure of Carbonized Rice Husk Briquetting burning from starting and final stage.

2.3. Experiment Design

The study methodically investigates the effects of clay soil binder ratios and compaction pressure levels on the burning characteristics of carbonized rice husk briquettes, including their burning temperature and duration. A factorial experimental design was adopted, featuring three levels of applied compaction pressure (6 mm, 12 mm, and 18 mm) and five ratios of clay soil as a binding agent (0%, 5%, 10%, 15%, and 20%). This 3 x 5 full-factorial design enabled the analysis of 15 treatment combinations, with each combination replicated three times, resulting in a total of 45 experimental units. The response variables—burning temperature and burning duration—were measured for each experimental unit to evaluate the thermal performance of the briquettes. Statistical methods were used to analyze the main effects of the clay soil binder and compaction pressure, as well as their interaction effects.

2.4. Variables and Data Collection

The research study centered on the thermal properties and quality of carbonized rice husk briquetting charcoal during combustion, specifically examining burning temperature and burning duration.

2.4.1. Independent Variables

The independent variables in this study consist of the characteristics of rice husk, the ratio of clay soil binding agent, and the level of applied compression pressure.

The rice husk was selected as the raw material for the experiment. It was meticulously cleaned to remove any foreign materials and dried to reduce the moisture content, directing for better and more complete carbonization. Successively, the paddy husk was changed into biochar through the process of carbonization [23].

Clay soil was specifically chosen as the binding agent for rice husk briquettes due to its easy availability. When combined with carbonized rice husk powder, it forms a cohesive mixture for compressed charcoal briquettes. In this experiment, five levels of clay soil binding ratios were tested with carbonized rice husk powder: 0% and 100%, 5% and 95%, 10% and 90%, 15% and 85%, and 20% and 80%.

The accurate application of compression pressure is crucial for consolidating the mixture of carbonized rice husk and binding material, ensuring the production of durable and resilient charcoal briquettes. Through the use of a hydraulic jack, the compaction level was meticulously regulated to reach the targeted density and structural strength of the briquettes. This meticulous control assurances that the briquettes not only retain their shape and quality but also burn efficiently. In this study, three specific levels of applied compaction pressure were selected, namely 6mm, 12mm, and 18mm.

A total of fifteen treatment combinations were conducted in this study, involving the clay soil binding agent in conjunction with applied compaction pressure levels. These combinations include 0% and 6mm, 5% and 6mm, 10% and 6mm, 15% and 6mm, 20% and 6mm, 0% and 12mm, 5% and 12mm, 10% and 12mm, 15% and 12mm, 20% and 12mm, 0% and 18mm, 5% and 18mm, 10% and 18mm, 15% and 18mm, and 20% and 18mm. Each combination was replicated three times to ensure the reliability and consistency of the results.

2.4.2. Dependent Variables

The variables under observation for the charcoal briquettes focus on the thermal attributes of carbonized rice husk briquettes. These encompass burning temperature, duration of burning at that temperature, and the application of regression models to develop predictive equations and graphical representations. These metrics are fundamental for evaluating the efficacy and functionality of the briquettes as a fuel source.

In the study, the burning temperature of charcoal derived from carbonized rice husks was examined in relation to different independent variables. Factors such as the composition of the rice husk, compaction pressure level of the briquettes, and binder of clay soil material ratio combustion were considered. The carbonization process, which entails heating the rice husks in the absence of oxygen, results in the conversion of the organic material into a more carbon-rich and energy-dense form.

The transformation of rice husks into carbonized briquetting charcoal not only enhances burning efficiency but also contributes to reducing emissions associated with traditional fuels. To measure the burning temperature of the carbonized rice husk charcoal accurately, a K-type thermocouple was utilized to record the temperature at 1-second intervals. The recorded temperature values were then extracted from the thermocouple storage and transferred to a computer in Excel format. Each treatment involved replicating the temperature measurements three times.

The duration of burning temperature is the length of time that a carbonized rice husk briquetting charcoal maintains a specific temperature during combustion. This duration is influenced by the density of the briquettes and the presence of binders during the burning process. The time of duration recorded starting from the beginning to the end of the life span of the burning of briquetting charcoal. The time of duration was recorded by the K-type thermocouple device during recording temperature. Simultaneously, it is also recording the duration of the burning temperature at the time of the burning the briquetting charcoal. The data collected provides insights into the efficiency and effectiveness of the briquettes in maintaining a consistent heat output. Analyzing these temperature fluctuations can help in optimizing the formulation of the briquettes.

2.4.3. Data Analysis

The analysis of the correlation between time and temperature in a burning carbonized rice husk briquetting charcoal scenario was conducted using SPSS and Minitab 21 statistical software. Visual representation of the data was achieved through a regression model, with time and temperature plotted on the x-axis and y-axis respectively. The equation, determined by calculating the slope, time, and intercept, indicated the initial temperature of the charcoal at the beginning of the experiment. This comprehension of the relationship can offer valuable insights for chefs seeking to regulate the cooking process when utilizing charcoal grills. Furthermore, meticulous control and consideration of environmental factors such as airflow, humidity, and the charcoal type were integrated into the experimental design.

3. Result and Discussion

3.1. Regression Model of Burning Time and Temperature

The temperature of charcoal was modeled using regression analysis with time and temperature variables. Initially, a linear regression model was used, but the complex nature of the burning process required a switch to a polynomial regression model. The burning temperature and the duration of burning time are affected by the applied compaction pressure level and the binding clay soil agent ratio. The relationship between clay soil binding agent ratios and compaction pressure levels is decisive for optimizing the charcoal briquetting process. Detailed data collection, including precise monitoring of temperatures with advanced sensors, has provided valuable insights. The intricate nature of charcoal burning calls for a nuanced optimization approach, especially through the use of a polynomial regression model to accurately capture the process complexities.

3.2. Effects of Clay Soil Binding Agent Ratios at 6 mm Compaction Pressure Level

In the modeling equation 1 and figure 3 below, a strong correlation is observed between the compaction pressure level at 6 mm compaction pressure level and absence of clay soil binding (R^2= 98.95%). Low burning temperature (<110 ℃) and short burning time (<5 minutes) associated with binding agent. Inadequate compaction pressure and no binding agent result in incomplete combustion, weak structure, and decreased burning temperature and time.

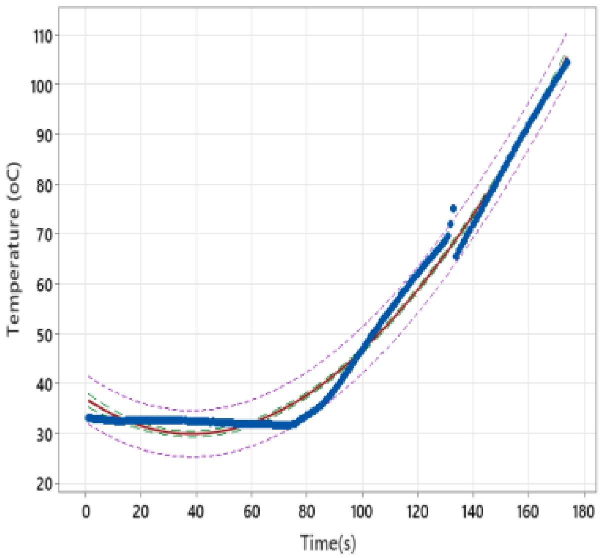

Figure 3. *Interaction Effects of Zero Clay Soil Binding at 6 mm Compaction Pressure Level on Burning Temperature and Burning Temperature Duration.*

In Figure 4 and Modeling Equation 2, the increase in the clay soil binding ratio to 5% significantly influenced burning temperature and duration. At this clay soil percentage, the regression line closely matched the observed values, achieving an impressive R^2 value of 92.30%. The burning temperature peaked above 965 ℃, accompanied by a burning duration exceeding 1.67 hours. The subsequent reduction and stabilization of the burning temperature, as illustrated in Figure 4, is attributed to variations in clay soil composition, heat retention properties, and the material's structural integrity.

$$T^{\circ} = 36.98 - 0.38t + 5.13x10^{-3}\,t^2 - 4.3x10^{-5}\,t^3 \quad (1)$$

$$T^{\circ} = 86.14 + 0.87t - 3.08x10^{-4}\,t^2 + 10^{-6}\,t^3 \quad (2)$$

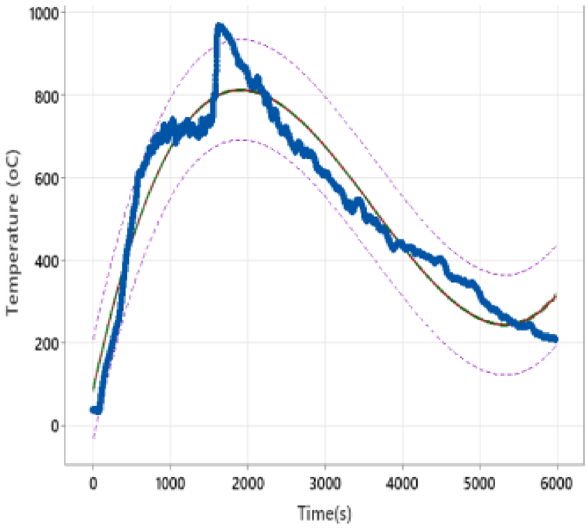

Figure 4. *Interaction Effects of 5% Clay Soil Binding ratio and 6 mm Compaction Pressure Level on Burning Temperature and Burning Temperature Duration.*

In modeling equation 3 and figure 5 provided below, the independent variables of the applied compaction pressure level of 6 mm and the binding clay soil agent ratio of 10% exert a profound influence on both the burning temperature of briquetting and its duration. The findings demonstrate a coefficient of determination value of 73.70%, indicating that a considerable portion of the variations in burning temperature and duration can be attributed to the specified independent variables. This level of determination indicates a moderately strong relationship between these factors and the outcomes measured.

$$T^{\circ} = 339.5 + 0.478t - 1.12x10^{-4}\,t^2 + 10^{-6}\,t^3 \quad (3)$$

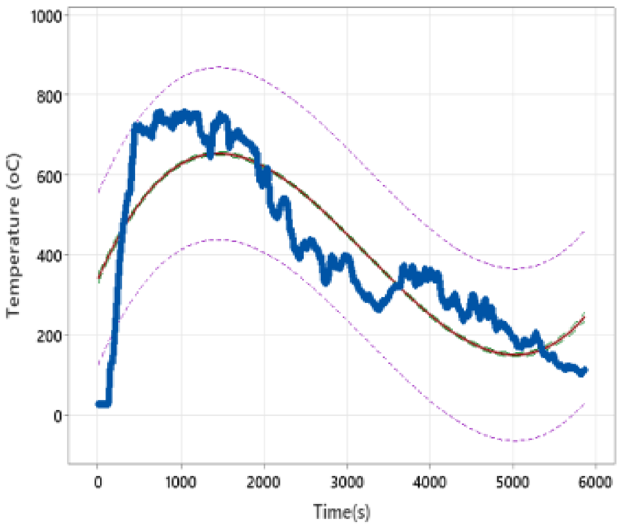

Figure 5. *Interaction Effects of 10% Clay Soil Binding ratio and 6 mm Compaction Pressure Level on Burning Temperature and Burning Temperature Duration.*

At a clay soil binding ratio of 15%, the R^2 value of 85.5% signifies a strong correlation between burning temperature and burning time. In this experimental treatment, both burning temperature and burning time outperformed all other treatments, with the burning temperature surpassing 972 degrees Celsius and the burning duration exceeding 1.70 hours. The figure 6 displays a distinct parabolic shape, indicating a gradual decline in temperature rather than a sudden decrease. The exceptional performance in both burning temperature and duration is attributed to the meticulous balance of applied compaction pressure levels with the percentage of clay soil binding ratio.

$$T^\circ = 322.7 + 0.721t - 2.72x10^{-4}\, t^2 + 10^{-6}\, t^3 \quad (4)$$

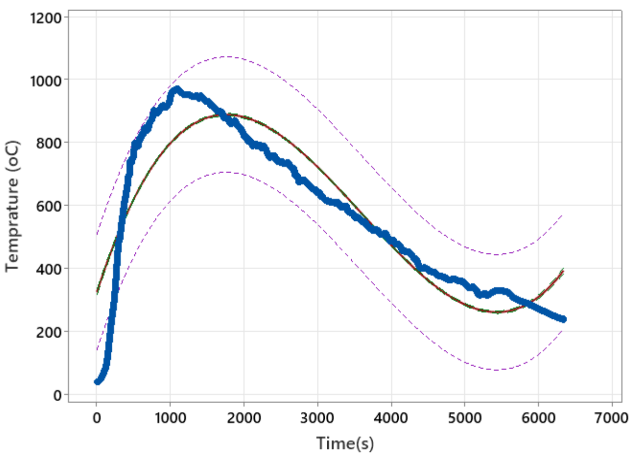

Figure 6. *Interaction Effects of 15% Clay Soil Binding ratio and 6 mm Compaction Pressure Level on Burning Temperature and Burning Temperature Duration.*

The applied compaction pressure level of 6 mm and a clay soil binding ratio of 20% significantly effect on the burning temperature and burning time of briquetting, as evidenced by the strong correlation with the R^2 value of 95.30%. This high R^2 value indicates a predictable and strong relationship between burning temperature and burning time, suggesting that an increase in burning temperature is likely to result in a corresponding increase in burning time. The regression model equation 5 provided, along with figure 7, further elucidates this relationship, offering insights into the precise effects of the compaction pressure level and clay soil binding ratio on the burning characteristics of the briquettes.

$$T^\circ = 162.1 + 0.693t - 2.51x10^{-4}\, t^2 + 10^{-6}\, t^3 \quad (5)$$

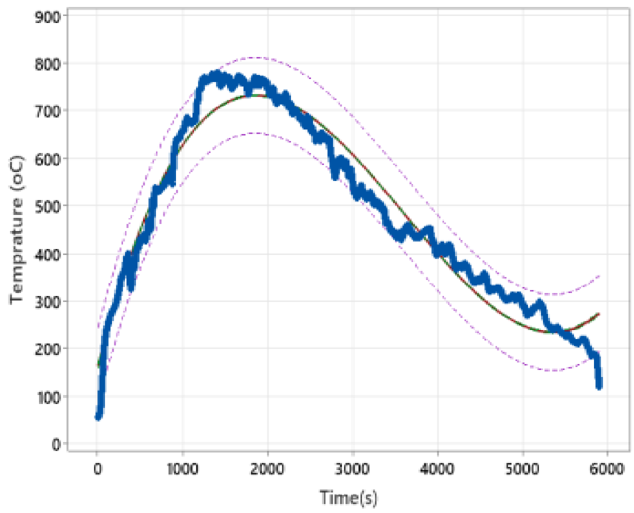

Figure 7. *Interaction Effects of 20% Clay Soil Binding ratio and 6 mm Compaction Pressure Level on Burning Temperature and Burning Temperature Duration.*

Figure 8 illustrates the combination interaction between varying percentages of clay soil binding ratios and a constant applied compaction pressure level of 6 mm. The output data reveal diverse correlations and models for burning temperature and burning time duration across the range of binding ratios. Notably, the burning temperature reaches its peak at a clay soil binding ratio of 15%, followed by 5%, 20%, 10%, and 0%, with the latter producing the lowest temperature. This demonstrates that applying a compaction pressure of 6 mm alongside a 15% clay soil binding ratio achieves the most balanced and optimal results, with the highest burning temperature and prolonged burning time duration. Accordingly, this combination is recommended for maximizing both burning temperature and duration. These findings are consistent with those reported by [10, 6, 28, 19].

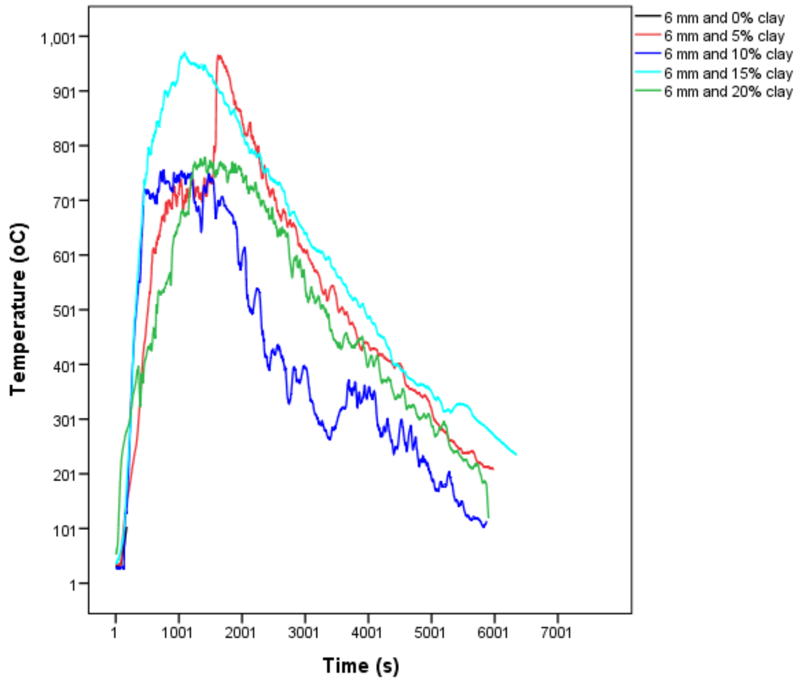

Figure 8. Interaction Effects of 0%, 5%, 10%, 15% and 20% Clay Soil Binding Ratios and 6 mm Compaction Pressure Level on Burning Temperature and Burning Temperature Duration.

3.3. Effects of Clay Soil Binding Agent Ratios at 12 mm Compaction Pressure Level

The modeling results reveal a significant association between the compaction pressure level of 12 mm and the percentage ratios of clay soil binding agent (0%, 5%, 10%, 15%, and 20%) in relation to the burning temperature and burning time duration of carbonized rice husk briquetting charcoal.

The regression modeling equation 6 and accompanying figure 9 illustrate that utilizing a compaction pressure of 12mm with a clay soil binding ratio of zero leads to insignificant burning temperature and burning duration outcomes. The coefficient of determination value of 81.22% indicates a moderately strong correlation between these variables. In circumstances where no binding agent is incorporated, the carbonized rice husk briquetting charcoal structures exhibit poor cohesion and lack strength, impeding their capacity to achieve the required burning temperature. The analysis reveals that this treatment combination does not produce burning temperatures surpassing 160 degrees Celsius or burning durations exceeding 33.34 minutes.

Regression modeling, as presented in Figure 10 and Equation 7, highlights a significant positive correlation between a 5% clay soil binding agent ratio and both the predicted burning temperature and duration of carbonized rice husk briquetting charcoal. The model demonstrates a strong alignment with experimental data, supported by an R^2 value of 91.17%, indicating a robust correlation. Utilizing a 12 mm compaction pressure combined with a 5% clay soil binding agent ratio emerges as an optimal configuration, delivering favorable burning temperature outcomes and an extended burning duration of approximately 1.67 hours.

$$T^{\circ} = 23.76 + 0.228t - 1x10^{-4}t^2 + 10^{-6}t^3 \quad (6)$$

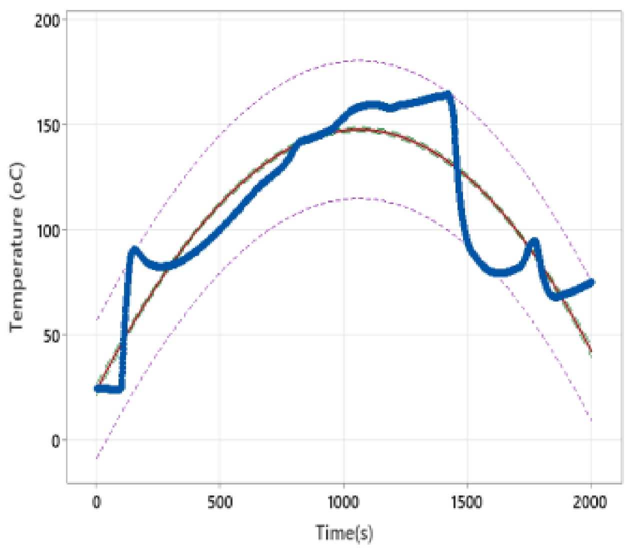

Figure 9. Interaction Effects of 0% Clay Soil Binding ratio and 12 mm Compaction Pressure Level on Burning Temperature and Burning Temperature Duration.

$$T^{\circ} = 314 + 0.727t - 2.36x10^{-4}t^2 + 10^{-6}t^3 \quad (7)$$

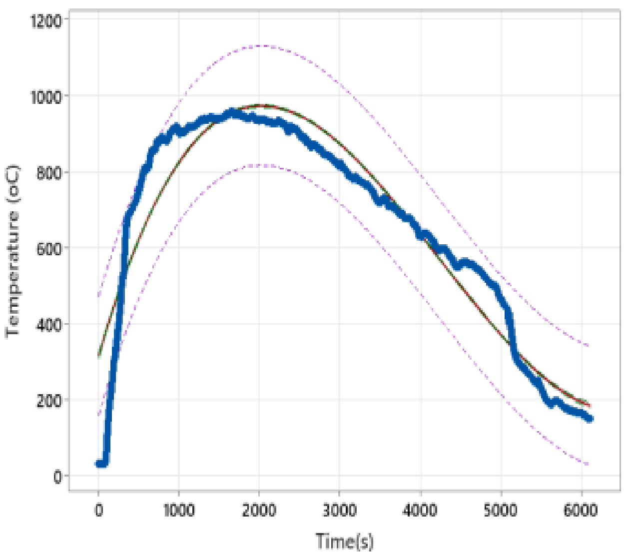

Figure 10. *Interaction Effects of 5% Clay Soil Binding ratio and 12 mm Compaction Pressure Level on Burning Temperature and Burning Temperature Duration.*

$$T^{\circ} = 785.3 + 0.03t - 8.8x10^{-5}\, t^2 + 10^{-6}\, t^3 \quad (8)$$

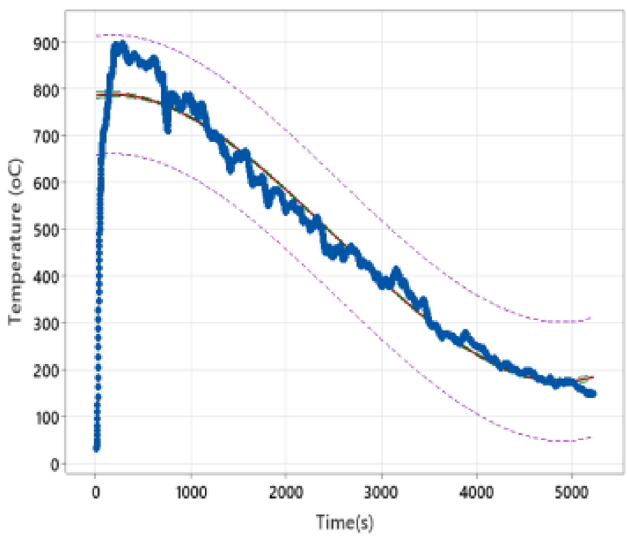

Figure 11. *Interaction Effects of 10% Clay Soil Binding ratio and 12 mm Compaction Pressure Level on Burning Temperature and Burning Temperature Duration.*

In modeling Equation 8 and Figure 11, the burning temperature and burning time results are analyzed at a 10% clay soil binding agent ratio under an applied compaction pressure level of 12 mm. The regression model demonstrates a strong coefficient of determination, with an R^2 value of 92.30%, indicating a robust correlation between the anticipated burning temperature and burning duration. The burning temperature exhibited a significant peak during combustion but decreased rapidly following the peak output.

$$T^{\circ} = 285 + 0.68t - 2.79x10^{-4}\, t^2 + 10^{-6}\, t^3 \quad (9)$$

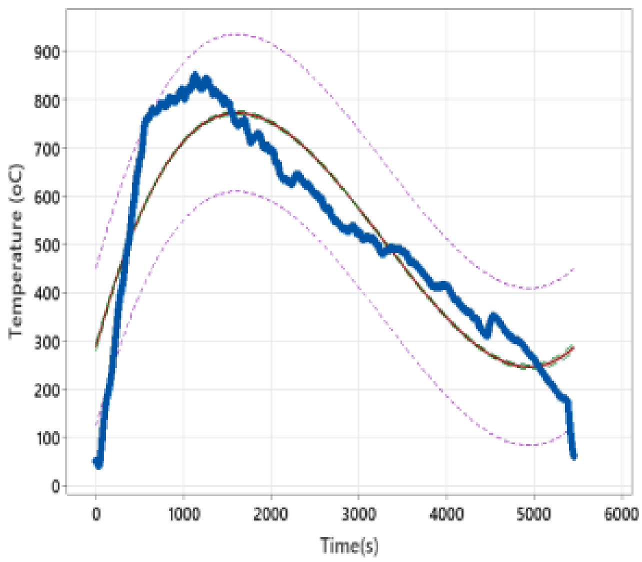

Figure 12. *Interaction Effects of 15% Clay Soil Binding ratio and 12 mm Compaction Pressure Level on Burning Temperature and Burning Temperature Duration.*

The polynomial regression model, as represented by Equation 9 and Figure 12, demonstrates the effect of a 15% clay soil binding agent ratio under an applied compaction pressure level of 12 mm on the dependent variables: burning temperature and burning duration of carbonized rice husk briquetting. With an R^2value of 83.9%, the model effectively explains the variance in burning temperature relative to time duration, highlighting its predictive strength for temperature changes and optimization of the briquetting process. This predictive capability facilitates precise adjustments to manufacturing parameters, enhancing both the quality and efficiency of the final product.

The regression model detailed in equation 10 and illustrated in figure 13 provided offers a precise representation of the association between the burning temperature of carbonized rice husk briquettes and the duration of burning, with a notably high R^2value of 94.4%. The coefficient of determination demonstrates a strong correlation between the burning temperature and the duration of burning, accounting for the applied compaction pressure of 12 mm and the inclusion of a 20% clay soil binding agent. The high R^2value underscores that the variability in burning temperature is predominantly explained by the burning duration, signifying a robust predictive relationship.

$$T^{\circ} = 438.7 + 0.344t - 1.17x10^{-4}\, t^2 + 10^{-6}\, t^3 \quad (10)$$

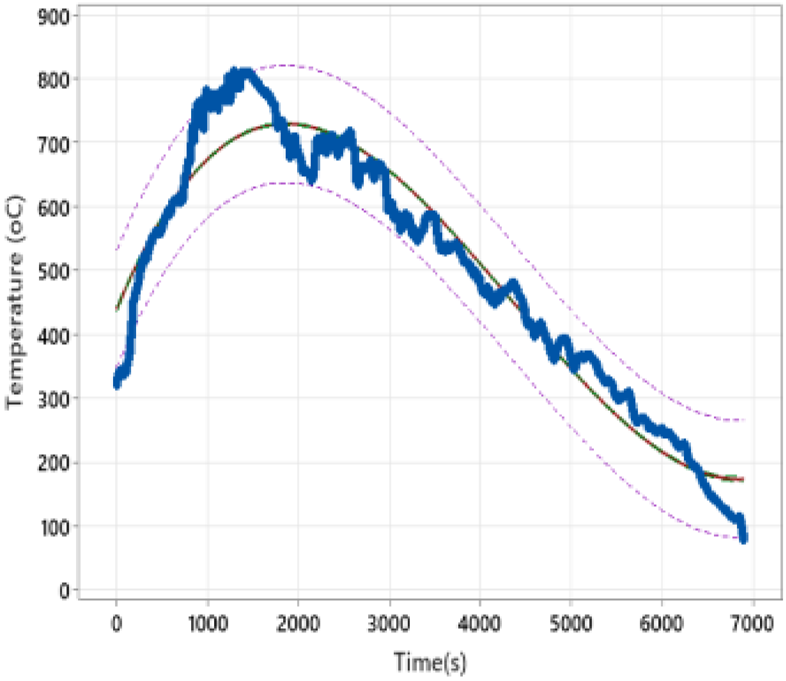

Figure 13. Interaction Effects of 20% Clay Soil Binding ratio and 12 mm Compaction Pressure Level on Burning Temperature and Burning Temperature Duration.

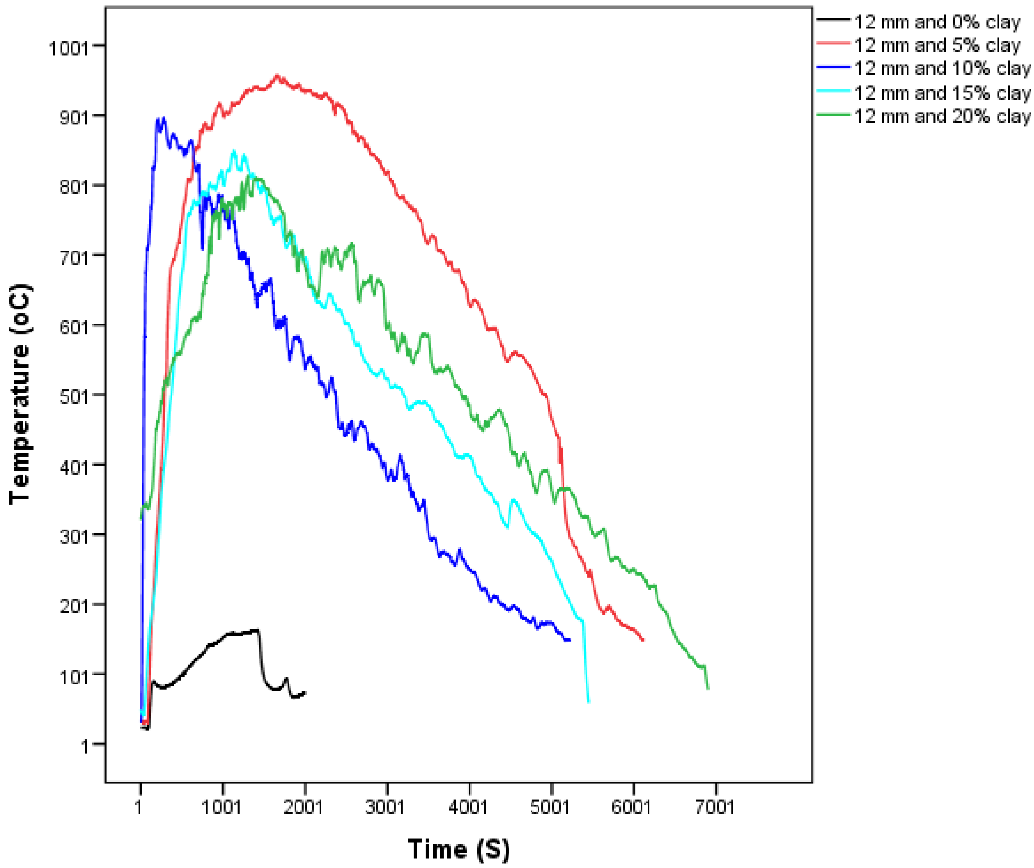

Figure 14. Interaction Effects of 0%, 5%, 10%, 15% and 20% Clay Soil Binding Ratios and 12 mm Compaction Pressure Level on Burning Temperature and Burning Temperature Duration.

The grouping figure 14 illustrates the association between increasing percentages of clay soil binding ratio and a constant applied compaction pressure level of 12 mm. The outputs for burning temperature and burning time duration display varied correlations and models across the range of binding ratios. The combination modeling results reveal that the burning temperature peaks at a clay soil binding ratio of 5%, which at a minimum clay soil binding of 5% is the output of burning temperature of the carbonized rice husk briquetting charcoal maximum yield, and at 20% of clay soil binding agent ratio the burning temperature a little bit deviates from 5% clay soil binding ratio at the commencement stage. Hence, the burning duration in this treatment is extended, leading to a gradual reduction in the burning temperature, which sets it apart from other treatments that endure longer burning periods of more than 1.95 hours. At 10% and 15%, the clay soil binding agent reaches peak position but immediately falls down, not staying more time at peak burning temperature. While the binding ratio of clay soil at zero percent, the output of the burning temperature, and the duration of the burning period are very low, it is already valueless. From the treatments, a 5% clay soil binding agent ratio resulted in the maximum burning temperature, while a 20% clay soil binding agent ratio ensured a longer burning duration. At the minimum clay soil binding ratio and a medium level of compaction pressure, the burning temperature output was highest. This outcome demonstrates that a lower clay soil binding ratio minimizes ash content, leading to a significantly higher burning temperature. Additionally, the medium compaction pressure optimizes density and porosity, ensuring adequate airflow and achieving the highest burning temperature. This finding is consistent with the studies conducted by [11, 7, 27, 1, 29, 3].

3.4. Effects of Clay Soil Binding Agent Ratios at 18 mm Compaction Pressure Level

The modeling results indicate a sturdy association between the compaction pressure level of 18 mm and the proportion of clay soil binding agent at various percentages (0%, 5%, 10%, 15%, and 20%) of the burning temperature and duration of carbonized rice husk briquettes. This implies that the different treatment combinations exhibit significant correlated effects.

In the modeling equation 11 and modeling figure 15 presented, the compaction pressure at 18 mm without a clay soil binding ratio results in a coefficient of determination of 78.95%. However, with a burning temperature of approximately 700 degrees Celsius, the maximum burning time duration is 41.67 minutes. This treatment combination is deemed unfeasible due to inadequate strength in briquetting and substandard structure formation.

$$T^{\circ} = 396.3 + 0.458t - 3.34x10^{-4}t^{2} + 10^{-6}t^{3} \quad (11)$$

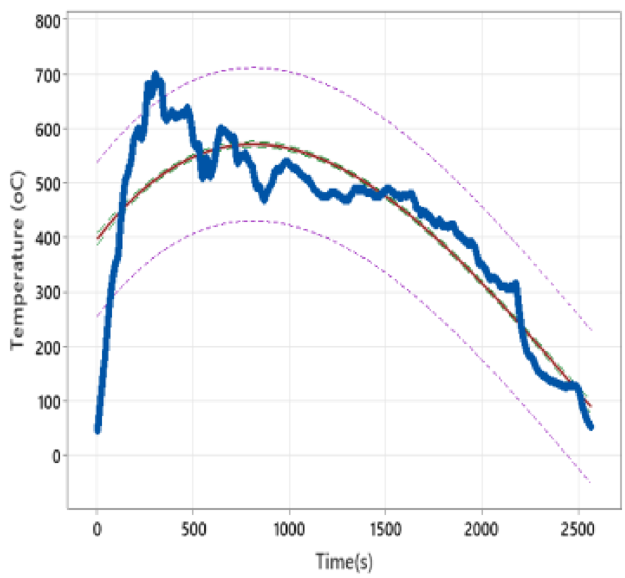

Figure 15. *Interaction Effects of 0% Clay Soil Binding ratio and 18 mm Compaction Pressure Level on Burning Temperature and Burning Temperature Duration.*

$$T^{\circ} = 546.4 + 0.337t - 1x10^{-4}t^{2} + 10^{-6}t^{3} \quad (12)$$

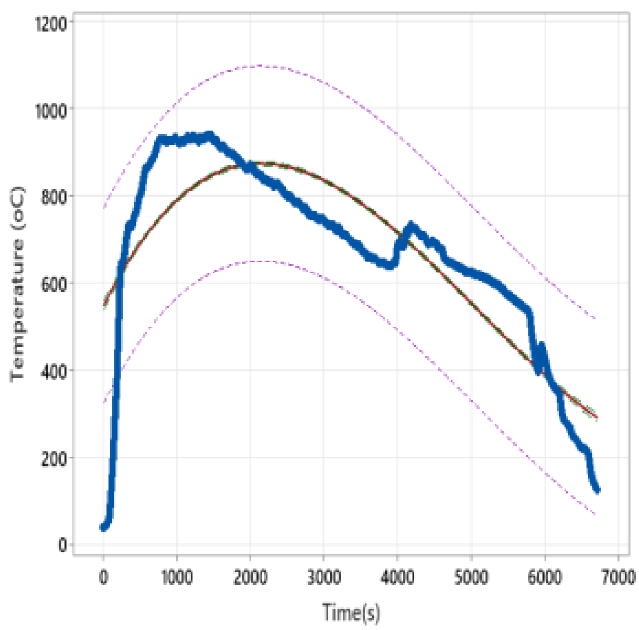

Figure 16. *Interaction Effects of 5% Clay Soil Binding ratio and 18 mm Compaction Pressure Level on Burning Temperature and Burning Temperature Duration.*

In the modeling presented in equation 12 and figure 16, the effects of an applied compaction pressure of 18 mm and a clay soil binding ratio of 5% on the burning temperature and burning duration of carbonized rice husk briquette charcoal were analyzed. The coefficient of determination (R^2) indicates a moderate correlation of 70.79%, comparing observed values with predicted outputs. While the actual burning temperature values show some deviation from the predicted model output, the burning duration.

The polynomial regression model equation 13 and figure 17 displays the compaction pressure applied at 18 mm and the 10% clay soil binding agent, showcasing their interaction effects on the burning temperature and burning time duration of the carbonized rice husk briquetting charcoal. In this regression modeling treatment, the coefficient of determination value is 95.28%, indicating a strong correlation between the variables, which indicates that the regression model is a reliable tool for predicting and controlling the burning characteristics of the charcoal. Even this harmonized treatment combination gives a good burning temperature, and the burning temperature lasts more than 1.9 hours.

$$T° = -42.38 + 0.896t - 2.58x10^{-4}t^2 + 10^{-6}t^3 \quad (13)$$

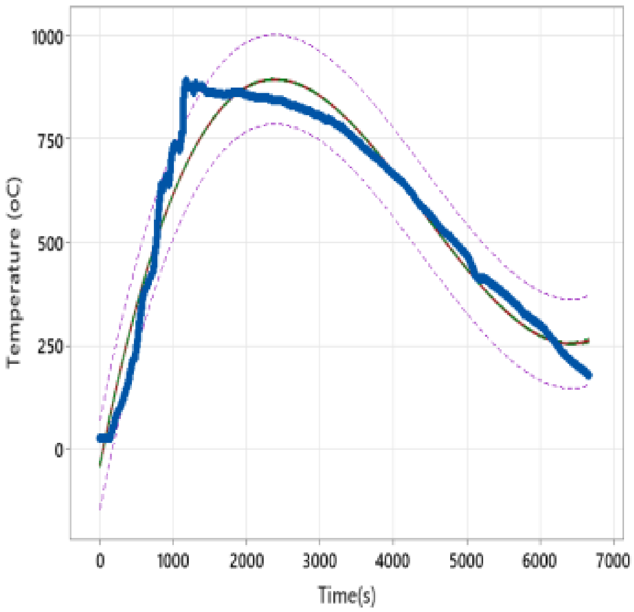

Figure 17. Interaction Effects of 10% Clay Soil Binding ratio and 18 mm Compaction Pressure Level on Burning Temperature and Burning Temperature Duration.

The polynomial regression model equation 14 and corresponding figure 18 visually represent the combined effect of compaction pressure at 18 mm and the inclusion of a 15% clay soil binding agent on the burning temperature and burning duration of carbonized rice husk briquettes. The high coefficient of determination value of 87.56% in this regression analysis indicates a significant and healthy relationship between the predicted burning temperature and the duration of burning. This correlation recommends that as the compaction pressure and clay soil content are optimized, both the burning temperature and duration can be effectively controlled to enhance the performance of carbonized rice husk briquettes.

$$T° = -35.66 + 1.186t - 5.07x10^{-4} t^2 + 10^{-6} t^3 \quad (14)$$

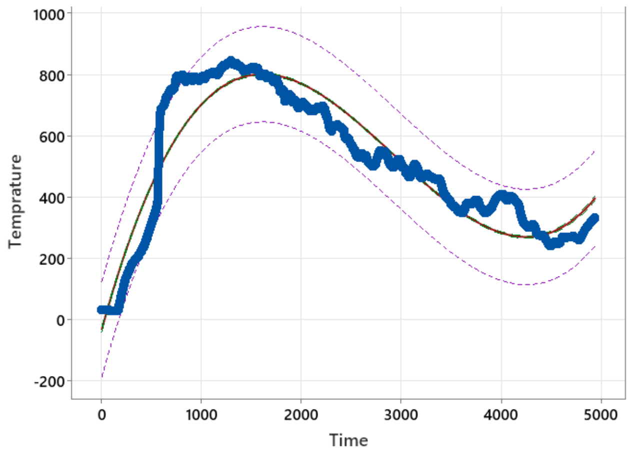

Figure 18. Interaction Effects of 15% Clay Soil Binding ratio and 18 mm Compaction Pressure Level on Burning Temperature and Burning Temperature Duration.

$$T° = 2.38 + 0.582t - 1.57x10^{-4} t^2 + 10^{-6} t^3 \quad (15)$$

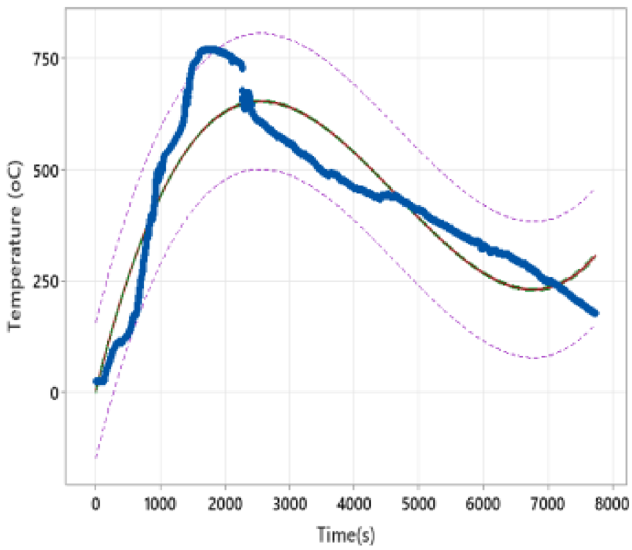

Figure 19. Interaction Effects of 20% Clay Soil Binding ratio and 18 mm Compaction Pressure Level on Burning Temperature and Burning Temperature Duration.

The polynomial regression model equation 15 and the Figure 19 that goes with it show how the compaction pressure at 18 mm and a 20% clay soil binding agent effect the temperature at which carbonized rice husk briquettes burn and how long they burn for. The R^2 value of 82.17% in this regression analysis indicates a significant and moderate relationship between the predicted burning temperature and the duration of burning. The high R^2 value of 82.17% in the regression analysis indicates that the model can effectively capture and explain a substantial portion of the variability in burning temperature and duration based on the input variables.

The results presented in modeling Figure 20, which maintained a constant compaction pressure level of 18 mm while varying the clay soil binding percentages (0%, 5%, 10%, 15%, and 20%), indicate that the burning temperature reaches its peak at a clay soil binding ratio of 5%. This ratio corresponds to the optimal output for achieving the maximum burning temperature yield. Additionally, a notably high burning temperature is observed at a clay soil binding ratio of 10%. At lower clay soil ratios, the briquettes retain higher amounts of fixed carbon and lower ash content, improving their combustion efficiency and heat generation capabilities, which result in higher burning temperatures. However, the longest duration of sustained high burning temperature was recorded at the maximum clay soil binding ratio of 20%. In this specific treatment combination, the briquettes achieved more than two hours of sustained high burning temperature. This phenomenon can be attributed to the combination of a highly compacted pressure level and a high clay soil binding ratio of 20%, which together produce a denser matrix that enhances the material's thermal stability and allows it to withstand extended exposure to high temperatures. The findings are reliable with those of scientists such as [2, 17, 8, 29, 18, 16].

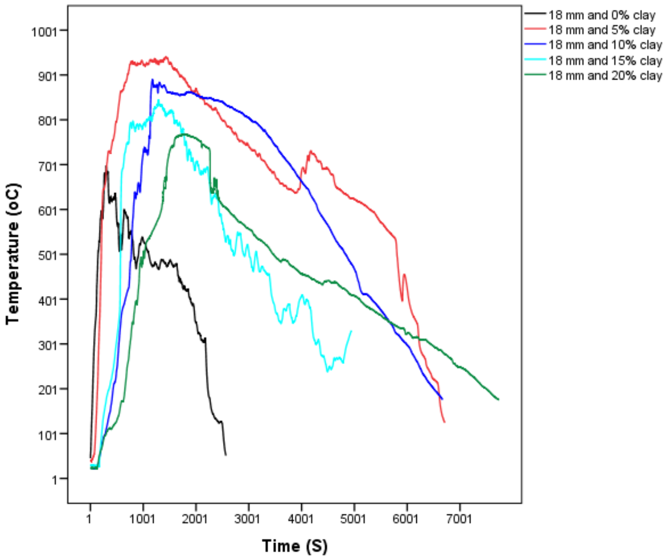

Figure 20. *Interaction Effects of 0%, 5%, 10%, 15% and 20% Clay Soil Binding Ratios and 18 mm Compaction Pressure Level on Burning Temperature and Burning Temperature Duration.*

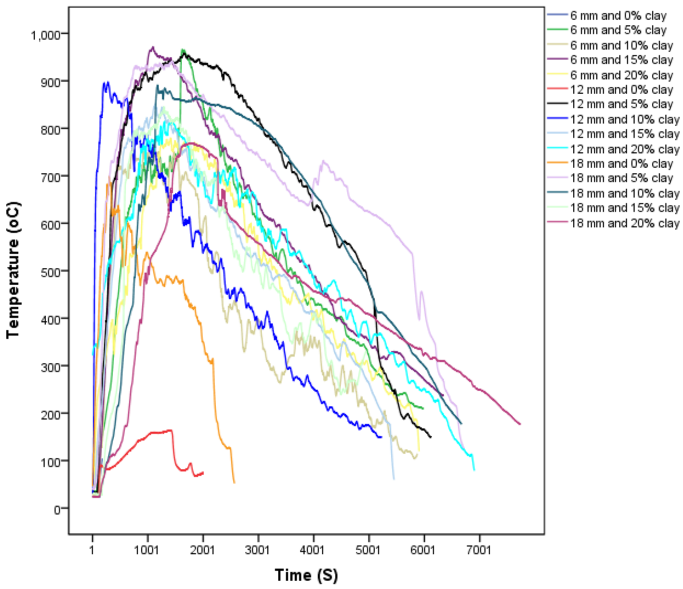

Figure 21. *Interaction Effects of 0%, 5%, 10%, 15% and 20% Clay Soil Binding Ratios and 6mm, 12mm and 18 mm Compaction Pressure Level on Burning Temperature and Burning Temperature Duration.*

The overall polynomial regression modeling in Figure 21 illustrates the combined effect of compaction pressure levels (6 mm, 12 mm, and 18 mm) and clay soil binding agent ratios (0%, 5%, 10%, 15%, and 20%) on the burning temperature and burning duration of carbonized rice husk briquettes. A total of 15 treatment combinations were analyzed. The peak burning temperature was observed at the treatment combination of a 6 mm compaction pressure level with a 10% clay soil binding agent ratio. For an extended burning duration, the peak burning temperature was recorded at the treatment combination of a 12 mm compaction pressure level with a 5% clay soil binding agent ratio. Moreover, a burning temperature duration exceeding two hours was achieved at the treatment combination of an 18 mm compaction pressure level with a 20% clay soil binding agent ratio. These findings highlight the significant influence of compaction pressure and clay soil binding agent ratios on the burning temperature and duration of carbonized rice husk briquettes.

4. Conclusion and Recommendation

The object of the study was evaluating and modeling the effect of clay soil binding ratio and compaction pressure level on the carbonized rice husk briquetting charcoal burning temperature and duration. The parameters are burning temperature and burning time duration of the carbonized rice husk briquetting charcoal on the factors of applied compaction pressure levels 6mm, 12 mm, and 18mm combined with the binding clay soil ratio of 0%, 5%, 10%, 15%, and 20%.

At a compaction pressure level of 6 mm without the inclusion of a clay soil binding agent, the coefficient of determination (R^2) value, which indicates a strong correlation, was 98.95%. Under this treatment, the insufficient compaction pressure combined with the absence of a binding agent resulted in incomplete combustion, a fragile briquette structure, and reduced performance, with a burning temperature of less than 110 ℃ and a burning duration of less than 5 minutes. In contrast, a treatment combination of a 6 mm compaction pressure level with a 15% clay soil binding ratio yielded an R^2 value of 85.50%, indicating a moderate correlation. This combination achieved a balanced and optimal outcome, producing the highest burning temperature exceeding 972 ℃ and an extended burning duration surpassing 1.70 hours.

In the treatment combination of a 12 mm compaction pressure level with a zero percent clay soil binding agent ratio, the coefficient of determination (R^2) is 81.22%, reflecting a moderate correlation. This combination produces a burning temperature that stays significantly low, under 160 ℃, and a brief burning duration, restricted to just 41 minutes. In contrast, the treatment combination of a 12 mm compaction pressure level with a 5% clay soil binding agent ratio achieves an R^2 value of 91.17%, denoting a strong correlation between burning temperature and burning duration. This combination produces a maximum temperature nearing 1000 ℃ and extends the burning duration to approximately 1.67 hours. Furthermore, the treatment combination of an 12 mm compaction pressure level with a 20% clay soil binding agent ratio exhibits an impressive R^2 value of 94.4%, indicating a high level of correlation. This combination delivers a burning duration that exceeds 1.94 hours.

Under the treatment combination of an 18 mm compaction pressure level with no clay soil binding agent, the regression model indicates brief burning temperature duration of approximately 41.67 minutes. The highest burning temperature is attained with an 18 mm compaction pressure level and a 5% clay soil binding ratio, reflected by a moderately high R^2 value of 78.95%. Meanwhile, the treatment involving an 18 mm compaction pressure level and a 20% clay soil binding ratio achieves the longest burning duration, surpassing two hours. This combination also demonstrates a strong correlation, as evidenced by an R^2 value of 82.17%.

In general across the 15 treatment combinations, the highest burning temperature was recorded with a 6 mm compaction pressure level and a 10% clay soil binding ratio. For prolonged burning duration, the peak burning temperature was achieved at a 12 mm compaction pressure level combined with a 5% clay soil binding ratio. Moreover, a burning duration exceeding two hours was observed with an 18 mm compaction pressure level and a 20% clay soil binding ratio.

Based on the findings, it is advisable to prioritize the treatment combinations of a 6 mm compaction pressure level with a 10% clay soil binding ratio and a 12 mm compaction pressure level with a 5% clay soil binding ratio to achieve the highest burning temperatures. For extended burning durations, the treatment combination of an 18 mm compaction pressure level with a 20% clay soil binding ratio is recommended. Future research could focus on evaluating alternative binder materials, varying compaction pressures, and utilizing diverse agricultural crop residues as potential sources for briquetting charcoal. Furthermore, examining different moisture content levels and particle sizes may offer valuable insights into enhancing the burning properties and overall efficiency of the briquettes.

Abbreviations

mm	Mille Meter
T	Time
T	Temperature
SPSS	Statistical Package for Social Science

Author Contributions

Mersha Alebachew Fetene: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing - original draft, Writing - review & editing

Dessye Belay Tikuneh: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing - original draft, Writing - review & editing

Conflicts of Interest

The authors declare no conflicts of interest.

References

[1] Ali, A., Kumari, M., Manisha, Tiwari, S., Kumar, M., Chhabra, D., & Sahdev, R. K. (2024). Insight into the biomass-based briquette generation from agro-residues: challenges, perspectives, and innovations. *BioEnergy Research*, *17*(2), 816-856.

[2] Daniel, K. K., Siagi, Z. O., & Ogola, J. O. (2020). Effect of formulation, binder and compaction pressure of rice husk-bagasse briquettes on thermal and physical properties. *Journal of Scientific Research and Reports*, *26*(10), 38-53.

[3] Fetene, M. A., & Tikuneh, D. B. (2025). The Effect of Clay Soil Binding Agent Ratio and Compaction Pressure Level on the Physical Properties of Carbonized Rice Husk Briquettes. *Bioprocess Engineering*, *9*(1), 1-11.

[4] Hwang, Y.-M., Roh, J.-S., & Nam, G. (2024). Feasibility assessment of manufacturing carbonized blocks from rice husk charcoal. *Biomass Conversion and Biorefinery*, *14*(20), 26409-26414.

[5] Joseph, P., Roy, A., Lonn, E., Störk, S., Floras, J., Mielniczuk, L., Rouleau, J.-L., Zhu, J., Dzudie, A., & Balasubramanian, K. (2023). Global variations in heart failure etiology, management, and outcomes. *Jama*, *329*(19), 1650.

[6] Kipngetich, P., Kiplimo, R., Tanui, J. K., & Chisale, P. (2023). Effects of carbonization on the combustion of rice husks briquettes in a fixed bed. *Cleaner Engineering and Technology*, *13*, 100608.

[7] Kipngetich, P., Kiplimo, R., Tanui, J. K., & Chisale, P. C. (2022). Optimization of combustion parameters of carbonized rice husk briquettes in a fixed bed using RSM technique. *Renewable Energy*, *198*, 61-74.

[8] Liang, B., & Liu, X. (2023). Decoupling combustion characteristics of biomass pellets and their mixture with bituminous briquettes. *Environmental Technology & Innovation*, *32*, 103275.

[9] Lubwama, M., Birungi, A., Nuwamanya, A., & Yiga, V. A. (2024). Characteristics of rice husk biochar briquettes with municipal solid waste cassava, sweet potato and matooke peelings as binders. *Materials for Renewable and Sustainable Energy*, *13*(2), 243-254. https://doi.org/10.1007/s40243-024-00262-x

[10] Lubwama, M., Yiga, V. A., & Lubwama, H. N. (2022). Effects and interactions of the agricultural waste residues and binder type on physical properties and calorific values of carbonized briquettes. *Biomass Conversion and Biorefinery*, *12*(11), 4979-4999.

[11] Lubwama, M., Yiga, V. A., Muhairwe, F., & Kihedu, J. (2020). Physical and combustion properties of agricultural residue bio-char bio-composite briquettes as sustainable domestic energy sources. *Renewable Energy*, *148*, 1002-1016.

[12] Mehta, C. R., & Badegaonkar, U. R. (2023). *Sustainable management of crop residues in Bangladesh, India, Nepal and Pakistan: challenges and solutions*.

[13] Morimoto, K., Tsuda, K., & Mizuno, D. (2023). Literature review on the utilization of rice husks: focus on application of materials for digital fabrication. *Materials*, *16*(16), 5597.

[14] Nam, S., Torn, V., Choeung, C., & Cheng, H. (2024). The potential of rice husks for electrical energy generation in Cambodia. *Int J Electr Electron Res*, *12*, 611-616.

[15] ND, C. P., Kashyap, S., & Jarial, S. (2024). Agricultural Waste Management Through Crop Residue Management: Challenges, Solutions, and Technological Advancements. In *Exploring Waste Management in Sustainable Development Contexts* (pp. 170-181). IGI Global.

[16] Nganko, J. M., Koffi, E. P. M., Gbaha, P., Kane, M., Ndiaye, B., Faye, M., Nkounga, W. M., Tekounegning, C. T., Bile, E. E. J., & Yao, K. B. (2024). Modeling and optimization of compaction pressure, binder percentage and retention time in the production process of carbonized sawdust-based biofuel briquettes using response surface methodology (RSM). *Heliyon*, *10*(3).

[17] Obi, O. F., Pecenka, R., & Clifford, M. J. (2022). A review of biomass briquette binders and quality parameters. *Energies*, *15*(7), 2426.

[18] Ossei-Bremang, R. N., Adjei, E. A., Kemausuor, F., Mockenhaupt, T., & Bar-Nosber, T. (2024). Effects of compression pressure, biomass ratio and binder proportion on the calorific value and mechanical integrity of waste-based briquettes. *Bioresource Technology Reports*, *25*, 101724.

[19] Owino, C. A., Lubwama, M., Yiga, V. A., Were, F., Bongomin, O., & Serugunda, J. (2024). Mechanical and thermal properties of composite carbonized briquettes developed from cassava (Manihot esculenta) rhizomes and groundnut (Arachis hypogea. L.) stalks with jackfruit (Artocarpus heterophyllus) waste as binder. *Discover Applied Sciences*, *6*(8), 428.

[20] Ramírez, A. T. O., Tovar, M. R., & Silva-Marrufo, O. (2024). Rice husk reuse as a sustainable energy alternative in Tolima, Colombia. *Scientific Reports*, *14*(1), 10391.

[21] Roman, K., & Grzegorzewska, E. (2024). Biomass Briquetting Technology for Sustainable Energy Solutions: Innovations in Forest Biomass Utilization. *Energies*, *17*(24). https://doi.org/10.3390/en17246392

[22] Sanchez, P. D. C., Aspe, M. M. T., & Sindol, K. N. (2022). An overview on the production of bio-briquettes from agricultural wastes: methods, processes, and quality. *Journal of Agricultural and Food Engineering*, *1*, 36.

[23] Saravanan, A., & Kumar, P. S. (2022). Biochar derived carbonaceous material for various environmental applications: Systematic review. *Environmental Research*, *214*, 113857.

[24] Shimamoto, Y., & Suzuki, T. (2023). Generation of Electric Energy from Gasifying Rice Husk and Utilization of Its By-Products to Cementitious Materials. *International Conference on Bio-Based Building Materials*, 973-981.

[25] Sruthy, K. S., Puranik, S., Kumar, V., Kaushik, A., Vikram, K. V, Manoj, M., Shukla, L., Singh, S. K., & Kumar, A. (2024). Recent developments in microbial degradation of crop residues: a comprehensive review. *International Journal of Environmental Science and Technology*, 1-18.

[26] Sugie, S., & Maeda, H. (2024). Conversion of rice husks into carbonaceous materials with porous structures via hydrothermal process. *Environmental Science and Pollution Research*, *31*(33), 45711-45717.

[27] Sunnu, A. K., Adu-Poku, K. A., & Ayetor, G. K. (2023). Production and characterization of charred briquettes from various agricultural waste. *Combustion Science and Technology*, *195*(5), 1000-1021.

[28] Yiga, V. A., Nuwamanya, A., Birungi, A., Lubwama, M., & Lubwama, H. N. (2023). Development of carbonized rice husks briquettes: Synergy between emissions, combustion, kinetics and thermodynamic characteristics. *Energy Reports, 9*, 5977-5991. https://doi.org/10.1016/j.egyr.2023.05.066

[29] Yunusa, S. U., Mensah, E., Preko, K., Narra, S., Saleh, A., & Sanfo, S. (2024). A comprehensive review on the technical aspects of biomass briquetting. *Biomass Conversion and Biorefinery*, *14*(18), 21619-21644. https://doi.org/10.1007/s13399-023-04387-3

[30] Yusuf, M. A., Witdarko, Y., Parjono, Pamungkas, W. A., & Suryadi. (2023). Characteristics of Charcoal Briquettes from Rice Husk Waste with Compaction Pressure Variations as an Alternative Fuel. *Journal of Ecological Engineering*, *24*(4), 237--243. https://doi.org/10.12911/22998993/159966