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Optimization of Eco-Friendly Fuel Briquettes from Agricultural Residues for Technological Innovations in Efficient Home Heating

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ABSTRACT

Harnessing agricultural residues for clean thermal energy requires more than material substitution, it demands precision engineering. This work introduces a technology-driven pathway for briquette innovation by integrating advanced material selection with statistical process optimization to develop high-performance solid biofuels for domestic heating. Torrefied coconut shell (CNS) and rice husk (RHK) were blended with 10 wt% molasses and optimized using Response Surface Methodology (RSM) via Design-Expert® (v13.05) to assess the effects of feed composition and dwelling time on compressive strength and shatter resistance. A key technological breakthrough was identified: CNS functions not only as a raw component but as a natural reinforcement medium, exhibiting self-bonding capability due to its high lignin and carbon content. This intrinsic binding action minimizes reliance on external binders and enhances production efficiency. The optimised formulation (100:0 CNS:RHK at 202 g) delivered superior mechanical performance of 3.63 MPa compressive strength and 95.2% shatter resistance with strong statistical reliability (R^2 = 0.96). Beyond material performance, the study establishes a scalable framework in which statistical modeling replaces traditional trial and error fabrication, enabling predictable durability, improved combustion stability, and seamless integration with low-emission stove technologies. By transforming low value biomass into structurally optimized, energy efficient fuels, this research advances clean thermal technology development and accelerates the transition toward resilient, renewable household energy systems.

Keywords: *Briquettes, Torrefaction, Molasses, Compressive Strength, Response Surface Methodology, Shatter Index.*

Introduction

Household heating remains one of the most energy-intensive domestic activities, particularly in developing economies where biomass contributes over 60% of total thermal energy use [1]. Despite the availability of modern energy carriers, traditional fuels such as firewood, charcoal, and kerosene remain the primary sources of domestic heating due to their affordability and accessibility (World Health Organization). However, these fuels suffer from low combustion efficiency, incomplete burning, high particulate emissions, and substantial indoor air pollution, posing both environmental and public health risks. At the same time, vast quantities of agricultural residues, including rice husks, coconut shells, and corn cobs are either openly burned or left to decompose, representing a missed opportunity for sustainable energy recovery and contributing to local environmental degradation [2]. Converting these residues into densified briquettes has emerged as a promising pathway to improve heating efficiency, with advancements in carbonization, binder formulation, and compaction technologies significantly enhancing calorific value, ignition properties, mechanical durability, and handling performance [3].

Recent integration of response surface methodology (RSM) and machine learning based predictive models has enabled the precise optimization of critical process variables such as biomass ratio, compaction pressure, and dwell time, allowing briquettes to be tailored to specific energy profiles and appliance configurations [4]. Nevertheless, widespread adoption of high-performance biomass fuels remains constrained by inconsistency in product quality, driven by variations in feedstock composition, production practices, and the absence of standardized specifications [5]. Moreover, much of the literature remains focused on basic characterization proximate and ultimate analyses, calorific evaluations, and static strength testing without adequately linking these parameters to appliance compatibility or thermal performance under real operating conditions [6]. Limited consideration has also been given to synergistic design with modern low-emission stoves, controlled airflow systems, and thermally optimized combustion chambers, despite their importance in maximizing energy conversion and minimizing pollutants [7].

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Equally overlooked are storage stability, handling safety, and mechanical resilience during transport and use, even though compressive strength and shatter resistance are critical to maintaining fuel integrity [8]. Overcoming these shortcomings is essential for enabling circular economy models and reducing dependence on fossil-derived household fuels [9].

In response to these challenges, the present study investigates the optimization of eco-friendly briquettes derived from carbonized coconut shell and rice husk using molasses as a natural binder. RSM was employed to fine-tune production parameters with the objective of maximising compressive strength and shatter resistance, establishing these as core indicators of operational durability and application readiness. The methodology encompasses systematic material preparation and experimental testing (Section 2), followed by statistical modeling and validation of optimized conditions (Section 3). The findings are interpreted within the broader context of clean thermal energy strategies, highlighting practical implications for integration with low-emission domestic heating systems. The study concludes with performance insights and recommendations for accelerating large-scale deployment of next-generation biomass fuels (Section 4).

Literature review

Recent studies have emphasized the importance of binder selection in biomass briquette production, demonstrating that natural binders like molasses significantly enhance mechanical properties and combustion performance.[10] investigated the effects of varying molasses concentrations on bio charcoal briquettes from sawdust, finding that a 12.5% molasses binder improved compressive strength and calorific value, positioning such briquettes as viable alternatives to fossil fuels. Similarly, [11] evaluated briquettes made from construction and demolition waste using starch as a binder through carbonization and reported that both binder type and carbonization temperature significantly influence fuel quality, highlighting the need for careful optimization of binder formulations to maximize performance. Carbonization process optimization has also been a key focus, with [12] demonstrating that optimal pressing parameters 6 MPa pressure, 15% binder ratio, and 30 seconds dwell time produced briquettes with 45% fixed carbon and a heating value of 21 MJ/kg.[13] further confirmed the potential of agricultural residues as sustainable briquette feedstocks, showing their suitability for process heat and power generation while promoting environmentally responsible utilisation of biomass waste.

Enhancing energy efficiency and combustion characteristics has been a central objective in recent briquette research.[7] highlighted that integrating biomass briquettes into clean energy systems provides a low-emission alternative to traditional coal-based fuels, reducing environmental pollution.[14] corroborated these findings by optimizing briquetting parameters and demonstrating that briquettes outperform raw biomass in terms of combustion efficiency and emission reduction. Additionally, life cycle assessments conducted by [15] revealed that densified rice husk briquettes increased combustion efficiency by 20%, while [16] showed that corn cob briquettes with a 9% binder exhibited superior energy performance and lower gas emissions when used in improved stoves. Collectively, these studies emphasize the potential of briquettes to enhance energy efficiency and contribute to cleaner, more sustainable domestic heating.

Technological innovations in production processes have further strengthened the role of biomass briquettes in sustainable energy systems.[17] demonstrated that machine learning models, such as Random Forest, could predict and optimize briquette quality by analyzing physical, combustion, and emission properties, enabling consistent high-performance fuel production. [4] applied multi-response optimization to determine optimal operating parameters for charcoal briquettes, enhancing both quality and combustion characteristics. Despite these advancements, research gaps remain, including the need for standardized testing protocols, integration with advanced heating technologies, and evaluation of long-term environmental impacts of large-scale production. Addressing these gaps presents opportunities to further develop eco-friendly briquettes using natural binders, leverage machine learning for process optimization, and foster collaborations among researchers, policymakers, and industry stakeholders to standardize and commercialize high-quality biomass briquettes.

Materials and Methods

Samples collection and preparation

Figure 1a shows the rice husk (RHK) harvested from a small plantation in Ijagbo, Kwara State, while Figure 2a depicts the coconut shell (CNS) collected from local markets in Malete, with both locations situated in the North Central region of Nigeria. The samples were weighed into containers and sun-dried for three days at approximately 35 °C until all moisture content was removed. The coconut shells were initially crushed using a mortar and pestle to a particle size of 5–6 mm, then further milled at a local facility in Ipata Market, Ilorin, to achieve a finer particle size range of 1–3 mm. The milled material was sieved to ensure uniformity, yielding a final particle size (Xp) of 1–3 mm. The rice husk and coconut shell were processed to the same particle size range to maintain consistency in sample preparation, as illustrated in Figure 1b and Figure 2b. This procedure follows established biomass briquette preparation protocols to ensure reproducibility and reliable experimental outcomes [18].

Figure 1: (a) Collected coconut shell (CNS) sample and (b) milled CNS

Figure 2. (a) Collected rice husk (RHK) sample and (b) milled RHK

Experimental Set-Up and Procedure

The torrefaction apparatus consisted of a vertical fixed-bed reactor fabricated from stainless steel grade 202, with dimensions of 1300 mm (length) × 1250 mm (height) × 500 mm (diameter). A distribution plate was positioned inside the reactor above a horizontally oriented tubular heating element rated at 2000 W (220–240 V). The heating element was located 518 mm from the reactor base and had a diameter of 200 mm (see Figure 4a). Coconut shell (CNS) and rice husk (RHK) samples were charged into the reactor for thermal decomposition under an inert nitrogen atmosphere, following the experimental design for specified temperature and holding time conditions. Prior to heating, the reactor was purged with nitrogen gas to displace oxygen and minimise the risk of oxidation or unwanted combustion during operation. To compensate for convective heat losses, the controller setpoint was maintained at 255 °C, resulting in an effective torrefaction temperature of 220 °C within the reactor bed (i.e., a 35 °C offset). The samples were gradually heated while continuously exposed to nitrogen gas to ensure a stable inert environment. Safety measures implemented during operation included controlled heating via a PID temperature controller, continuous nitrogen purging to maintain inert conditions, and operation in an unconfined area to prevent the accumulation of flue gases. Electrical grounding of the heating system was ensured, and the reactor was allowed to cool naturally to ambient temperature before opening to avoid thermal hazards. A condenser unit, cooled using an ice salt bath chiller, was connected to the reactor to facilitate condensation of condensable vapours, while non-condensable gases were collected using a gas sampling system. After the prescribed holding time, the resulting char was removed from the reactor, allowed to cool, and then weighed. This procedure was repeated for all biomass samples at fixed heating times and torrefaction temperatures according to the experimental design. Product yields were subsequently calculated using Equations (2) – (3).

Torrefaction of Coconut Shell

Table 1: Torrefaction parameters for CNS and RHK samples

Biomass	Mass (g)	Particle Size (mm)	Torrefaction Temperature (°C)	Torrefaction Duration
Coconut Shell (CNS)	1250	1–3	220	45 minutes
Rice Husk (RHK)	1000	1–3	220	30 minutes

A total of 1,250 g of milled coconut shell (Figure 1b), with a particle size distribution of 1–3 mm, was introduced into the chamber of a fixed-bed reactor, as shown in Figure 3 and Figure 4a, and the operational parameters were maintained as outlined in Table 1. The reactor was then heated to a torrefaction temperature of 220 °C and held isothermally for 45 minutes to facilitate the thermochemical conversion of the biomass into biochar (Figure 4b). This torrefaction protocol was adapted with reference to the methodology reported by [19], who demonstrated that mild thermal pretreatment within the 200–250 °C range effectively enhances the carbon content and fuel properties of lignocellulosic residues.

Key Torrefaction Parameters:

1. Mass of CNS: 1250 g
2. Torrefaction Temperature (T): 220 °C
3. Torrefaction Duration (t): 45 minutes

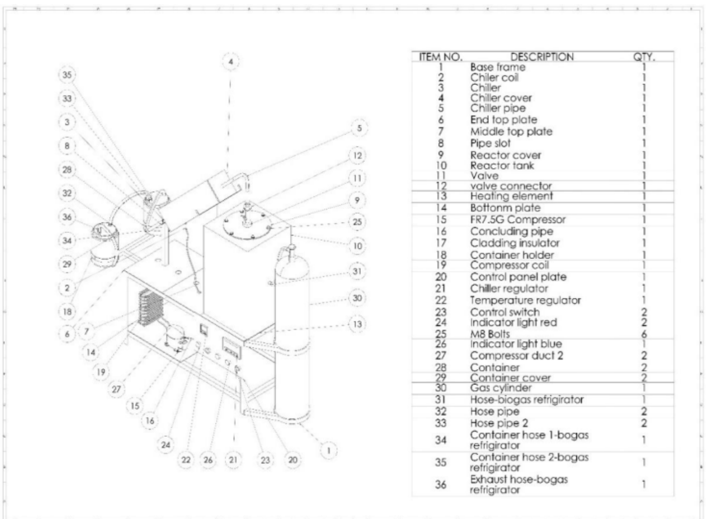

Figure 3: Assembly drawing of the fixed-bed reactor

Figure 4: (a) Fixed-bed reactor and (b) torrefied coconut shell (CNS) obtained at 220 °C for 45 minutes

Torrefaction of Rice Husk

A quantity of 1,000 g (Figure 2b) of milled rice husk (RHK) with a particle size range of 1–3 mm was loaded into the chamber of the fixed bed reactor. The reactor (Figure 4a) was set to a temperature of 220 °C, and torrefaction was carried out for 30 minutes to produce biochar (Figure 5), following the conditions summarised in Table 1. Similar torrefaction conditions have been widely reported in the literature for agricultural residues. For instance,[20] torrefied rice husk at 200–250 °C for 30–45 minutes and observed a significant improvement in energy density, while [21] applied a similar temperature range (220–260 °C) for coconut shell torrefaction. [22] demonstrated that biomass particle sizes between 1–3 mm improve heat transfer efficiency during torrefaction. These studies support the selection of 220 °C and 30 minutes as optimal process parameters for effective torrefaction.

Key Parameters for Initial Torrefaction:

1. Mass of coconut shell (CNS) torrefied: 1000 g
2. Torrefaction time (t): 30 mins
3. Torrefaction temperature (T): 220 °C

Figure 5: Rice husk (RHK) torrefied at 220°C for 30 minutes.

Production of briquettes from torrefied CNS and RHK

Weighing and mixing of Torrefied samples in ratios

After torrefaction, the coconut shell (CNS) and rice husk (RHK) were weighed, resulting in final masses of 1010 g and 850 g, respectively. For sample preparation, 202 g of torrefied CNS and 170 g of torrefied RHK were measured per batch. The molasses binder was quantified at 10 wt.% for all formulations (Figure 6a), while the total binder quantity procured for the experiments is shown in Figure 6b. Five different CNS–RHK mixing ratios were formulated to investigate the influence of blend composition on briquette characteristics. The detailed weight distribution of CNS, RHK, and binder across all sample sets is presented in Table 2.

Table 2: Composition and Weight Distribution of CNS-RHK Mixtures for Biochar Samples

Sample	Mixing Ratio (CNS: RHK)	CNS Weight (g)	RHK Weight (g)	Molasses (wt.%)
A	100:0	202.0	0	10%
B	75:25	151.5	50.5	10%
C	50:50	101.0	101.0	10%
D	25:75	50.5	151.5	10%
E	0:100	0.0	202.0	10%

Similar blending of coconut shell and rice husk biomass has been explored in recent studies [23]. Moreover, the use of molasses as a binder in biomass briquettes, especially with coconut shell, has been shown to improve physical and combustion properties [24]. In studies on mixed biomasses and binder effects, [25] demonstrated the effect of blend ratios and binder content on briquette strength and density using molasses in other biomass systems.

Figure 6. (a) weighing of 10 wt.% molasses for briquette formulation and (b) procured molasses quantity

Briquette Fabrication

The torrefied biomass samples, mixed uniformly with 10 wt.% molasses, were compressed into briquettes using a manual hydraulic briquette machine (Figure 7) at Kwara State University. This machine operates via a hydraulic-jack mechanism that applies substantial pressure to the biomass mixture in the compression chamber; the chamber is specifically designed to hold the torrefied samples securely, ensuring consistent compaction during the briquetting process. The Manual Hydraulic Briquette Machine in Operation (Figure 8) clearly illustrates this process.

Hydraulic pressing and related densification machines have been widely used and documented in recent studies, which report how pressure, dwell time, and press design influence briquette density and strength [26]. The use of molasses as a binder to improve the mechanical strength and combustion properties of briquettes has also been demonstrated [27]. Studies that combine torrefied biomass with mechanical pressing report improved physicomechanical durability and energy properties, supporting thkee approach used here [28].

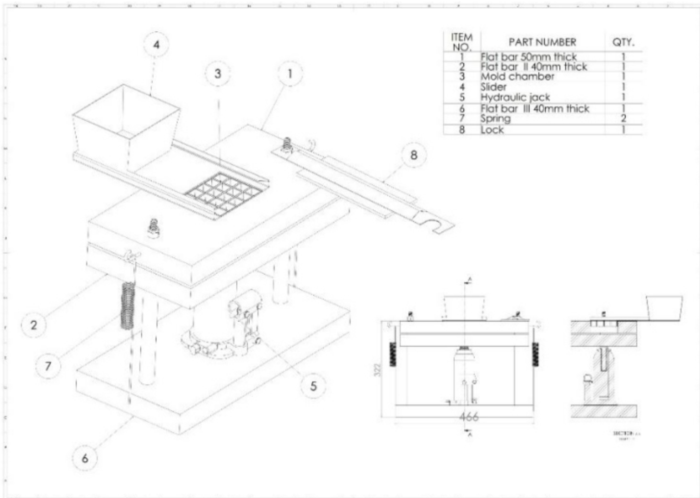

Figure 7: Assembly drawing of Manual hydraulic briquette machine

Figure 8: Manual Hydraulic Briquette Machine in Operations

Each briquette produced measures approximately 15 mm × 15 mm × 15 mm. Following production, the briquettes were sun-dried for seven (7) days to ensure complete removal of moisture content, enhancing their durability and combustion efficiency. The fabricated FBCS briquette samples (Figure 9) are shown immediately after production. The use of molasses as a natural binder improves the structural integrity of the briquettes, while the manual hydraulic press ensures uniform compression, resulting in consistent briquette density. Sun-drying not only reduces moisture but also helps prevent microbial degradation during storage.

Figure 9: Fabricated FBCS Briquette Samples

Analysis and Tests

Compressive Test

Compressive strength tests were carried out on coconut shell (CNS) and rice husk (RHK) briquette blends using a Universal Testing Machine (UTM) (Figure 10a) at the Department of Mechanical Engineering, Kwara State University. The objective was to assess the structural integrity and durability of the briquettes in order to identify the most suitable biofuel formulation. The experimental procedure followed ASTM D2166-85 (2008), utilizing a 5 kN load cell and a constant loading rate of 10 N/min until specimen failure. The control and data acquisition were managed by the computer interface (Figure 10b). This methodology is consistent with previous biomass briquette studies that adopted similar loading protocols for mechanical evaluation [29] [30]. Five CNS:RHK mixing ratios were tested: 100:0, 75:25, 50:50, 25:75, and 0:100 (Samples A–E) to enable comparative analysis. The corresponding compressive strength results for each sample are summarised in Table 3.

Table 3: Compressive strength of fabricated CNS–RHK briquette samples at different mixing ratios

Sample	CNS: RHK (%)	Compressive Strength (Mpa)
A	100:0	3.63
B	75:25	3.3
C	50:50	2.88
D	25:75	2.43
E	0:100	1.95

Figure 10: (a) Universal Testing Machine and (b) Computer interface and control system for data acquisition.

Shatter Index Test

The shatter test was conducted to determine the durability and impact resistance of the briquettes, reflecting their ability to withstand handling and transportation stresses. A briquette sample (15 × 15 × 5 mm) was dropped from a height of 5 m onto a concrete surface, and the resulting weight loss was recorded. Similar procedures have been reported in recent studies [30]. The shatter index (X) was calculated using Equation 1:

$$X = \frac{W_B - W_A}{W_B} \times 100 \quad (1)$$

Where W_B is the initial weight and W_A is the retained weight after impact. Lower X values indicate higher structural integrity, consistent with durability criteria established in previous works [30]. The observed durability and calculated shatter indices for the different CNS: RHK briquette blends are summarized in Table 4.

Table 4: Shattered index of fabricated CNS–RHK briquette samples at different mixing ratios

Sample	CNS:RHK (%)	Observed Durability	Shattered Index (%)
A	100:0	Very High	95.2
B	75:25	High	93.2
C	50:50	Moderate	88.0
D	25:75	Low	81.2
E	0:100	Very Low	74.0

Results and Discussion

Effect of Biomass Mixing Proportions on Compressive Strength

In this study, Design-Expert® software version 13.05 was used to perform Response Surface Methodology (RSM) to evaluate the influence of mixing proportions, specifically CNS (Coconut Shell) and RHK (Rice Husk Char) on the compressive strength of fabricated briquettes. By fixing other process parameters, including dwelling time, the 3D mix process surface plot generated in the software provided a clear visualization of the interactive effects of CNS and RHK on mechanical performance. As shown in Figure 11, compressive strength increased progressively with higher CNS content, highlighting its dominant role in enhancing structural integrity and densification. RHK exhibited a relatively minor effect, evident from the flatter slope along the RHK axis. The lowest compressive strength was observed in formulations with high RHK and low CNS content, emphasizing the importance of CNS in achieving robust briquettes. The linear response surface indicates a first-order relationship with minimal interaction between variables, validating the regression model and the predictive capability of RSM. The factor levels and corresponding response values for each experimental run are summarized in Table 5.

Table 5: Experimental design and measured responses for CNS–RHK briquette samples

	Factor 1	Factor 2	Factor 3	Response 1	Response 2
Run	A: CNS	B: RHK	C: Dwelling Time	Compressive Strength	Shattered Index
	G	G	s	Mpa	%
1	202	0	30	3.63	95.2
2	151.5	50.5	25	3.3	93.2
3	101	101	20	2.88	88
4	50.5	151.5	15	2.43	81.2
5	0	202	10	1.95	74

Beyond mechanical performance, the optimized CNS-RHK briquettes offer substantial advantages in terms of energy efficiency and sustainable energy applications. CNS-rich formulations demonstrate higher calorific values compared to traditional fuels such as untreated wood or raw agricultural residues, supporting more efficient combustion and improved energy output for home heating [31]. The use of agricultural residues also contributes to environmental sustainability by reducing waste and greenhouse gas emissions. Compared with advanced renewable energy systems, such as solar thermal or pelletized biomass technologies, these briquettes provide a low-cost, accessible, and practical solution for rural or off-grid communities.

Overall, the findings underscore that optimized CNS-RHK mixtures not only maximize mechanical durability but also enhance energy efficiency, highlighting their potential role in sustainable energy systems for domestic heating [32].

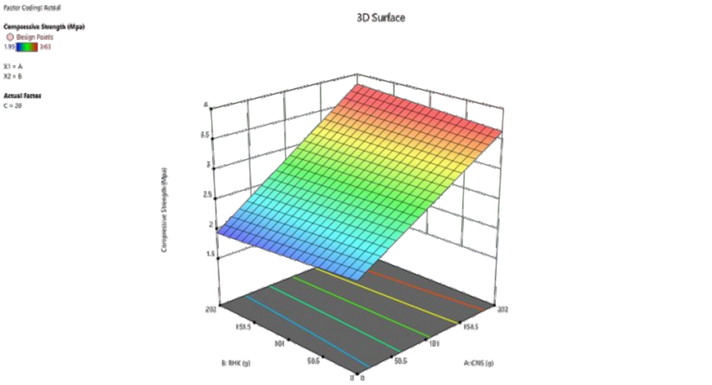

Figure 11: 3D Surface Response of Effect of Mixing Proportions & Binder on Compressive Strength of FBCS

Compressive Strength = +2.89 +0.8460A +0.0000B +0.0000C +0.0943AB +0.0000AC + 0.0000BC (2)

The constant term 2.89 is the predicted compressive strength at the center point of the design space when all coded variables are zero. The coefficient +0.8460A indicates that an increase in CNS content significantly increases compressive strength, showing that CNS plays a major role in bonding and structural integrity. The coefficients for B and C are 0.0000, implying that within the studied range, RHK content and dwelling time have no statistically significant individual effect on compressive strength. The interaction term +0.0943AB shows a positive combined effect between CNS and RHK, suggesting that their interaction slightly enhances the strength. The other interaction terms (AC, BC) also have coefficients of 0.0000, indicating no significant combined influence between those factors. Overall, this coded equation highlights that CNS content (A) and its interaction with RHK (AB) are the key contributors to improving compressive strength in the developed briquettes.
Similarly, [33] demonstrated that optimal compressive strength was more strongly correlated with binder efficiency and moisture content than with the base material composition. The relatively uniform compressive strength values observed in this study may be attributed to sufficient cohesion provided by the molasses binder across all CNS:RHK combinations, consistent with findings that molasses-bound briquettes exhibit minimal variation in strength when binder content is maintained at optimal levels. Thus, the observed surface response confirms that within the range investigated, the mechanical strength of the briquettes is stable and satisfactory, further validating molasses as an effective binding agent in agro-waste briquette formulations.

ANOVA for Quadratic Model

Based on the ANOVA results generated from Design-Expert® software (v13.0.5), the quadratic model for compressive strength was statistically significant, with an F-value of 4367.88 and a very low p-value (0.0002), indicating less than a 0.02% probability that the observed response occurred due to random noise. This confirms the robustness and predictive reliability of the model for evaluating the effects of CNS (Coconut Shell) and RHK (Rice Husk) on briquette strength. Among the model terms, factor A (CNS) and the interaction term A × B (CNS × RHK) were significant, with p-values of 0.0001 and 0.0254, respectively, demonstrating that CNS content and its interaction with RHK are the primary determinants of compressive strength. Factor B (RHK) and all quadratic terms (A^2, B^2, C^2), as well as other interaction terms (AC, BC), were non-significant or aliased, suggesting that they contributed minimally to the variation in compressive strength within the experimental range. The low residual mean square error (0.0002) further supports the adequacy of the model fit (Table 6).

Table 6: ANOVA for Quadratic model (Aliased)

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	1.80	2	0.8985	4367.88	0.0002	significant
A-CNS	1.79	1	1.79	8697.94	0.0001	
B-RHK	0.0000	0				
C-Dwelling Time	0.0000	0				
AB	0.0078	1	0.0078	37.81	0.0254	
AC	0.0000	0				
BC	0.0000	0				
A^2	0.0000	0				
B^2	0.0000	0				
C^2	0.0000	0				
Residual	0.0004	2	0.0002			
Cor Total	1.80	4				

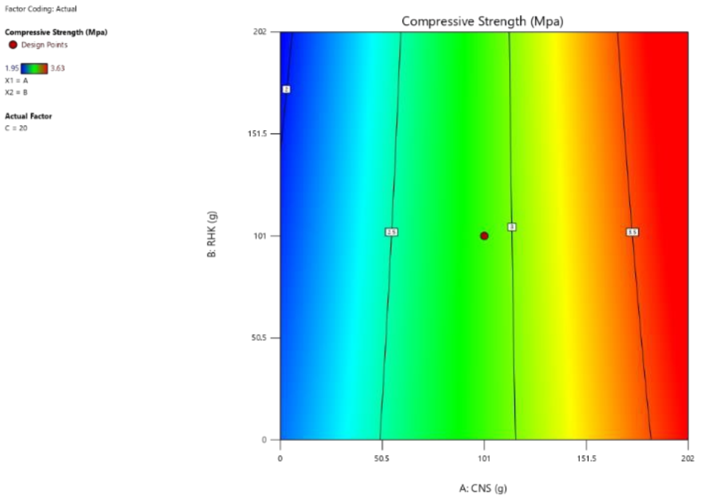

Figure 12: Contour Plot of Effect of Mixing Proportions & Binder on Compressive Strength of FBCS

The 3D and contour plots generated in Design-Expert® provide a visual representation of the interactive effects of CNS and RHK on compressive strength, highlighting the dominant role of CNS in enhancing structural integrity (Figure 12). While the model effectively predicts compressive strength within the studied range, it has limitations. The first-order linearity and exclusion of higher-order or non-linear interactions may reduce predictive accuracy for formulations outside the current design space. Additionally, fixed process parameters, such as dwelling time and binder content, constrain the generalizability of the model. Future studies could improve predictive capability by incorporating additional variables (e.g., pressing pressure, moisture content) and exploring higher-order or interaction effects in a larger experimental space. These findings are consistent with recent research highlighting the critical influence of feedstock proportions and interactions on the mechanical performance of biomass briquettes [5].

Fit Statistics Summary

The model's fit statistics confirm its robustness and predictive reliability for evaluating the compressive strength of briquette samples.

The low standard deviation (0.0143) and coefficient of variation (0.5054%) indicate high precision in the experimental measurements, consistent with acceptable precision criteria used in briquette optimization studies [33]. Furthermore, the R^2 (0.9998), adjusted R^2 (0.9995), and predicted R^2 (0.9964) are closely aligned, which aligns with model validation standards where minimal differences between adjusted and predicted R^2 values indicate strong predictive capability [34]. The Adequate Precision value of 152.2974, which substantially exceeds commonly accepted thresholds for RSM models, further confirms a high signal-to-noise ratio and demonstrates that the model can effectively navigate the design space for optimization. These statistical indicators are summarised in Table 7 and collectively support that the regression equation reliably predicts compressive strength as a function of CNS and RHK proportions, capturing the dominant influence of CNS content and its interaction with RHK on mechanical performance [33].

Table 7: The model's fit statistics

Std. Dev.	0.0143	R^2	0.9998
Mean	2.84	**Adjusted R^2**	0.9995
C.V. %	0.5054	**Predicted R^2**	0.9964
		Adeq Precision	152.2974

Effect of Biomass Mixing Proportions on Shattered Index

The shatter index of the fabricated briquettes was strongly influenced by the proportion of Coconut Shell (CNS), as revealed by the 3D response surface methodology (RSM) implemented in Design-Expert® software (version 13.05). Similar observations have been made in previous studies, where coconut shell-based briquettes exhibited high shatter resistance due to their lignin-rich and carbon-dense structure. In the present study, the 3D surface plot indicates that as CNS content increases, the shatter index rises correspondingly, reaching a maximum predicted value of approximately 97–100% at a CNS mass of 151.55 g (Figure 13). In contrast, Rice Husk (RHK) content exhibited a minimal effect on shatter index, aligning with findings by [35], who reported that low-density agricultural residues contribute to bulk but offer limited structural cohesion unless reinforced with a higher-carbon binder material. These results confirm that CNS serves as the primary reinforcement phase, while RHK functions more as a filler component rather than a structural enhancer.

Optimized briquettes offer several advantages over traditional fuels such as firewood, charcoal, and crop residues. High-CNS briquettes exhibit improved energy density and more uniform combustion, translating to higher thermal efficiency in domestic heating applications. Moreover, the use of bio-briquettes has been shown to reduce greenhouse gas emissions and indoor air pollutants compared to conventional fuels, supporting their role in clean energy transitions. While advanced systems such as solar thermal technologies offer long-term sustainability, biomass briquettes remain more immediately deployable in low-income and rural contexts. Therefore, the formulation insights gained from RSM not only optimise mechanical properties but also enhance the practical applicability of briquettes as a sustainable, high-performance biofuel for domestic heating and small-scale energy systems. The contour plot further illustrates the effect of CNS and RHK proportions on shatter index, highlighting the dominance of CNS and minimal influence of RHK within the studied range (Figure 14).

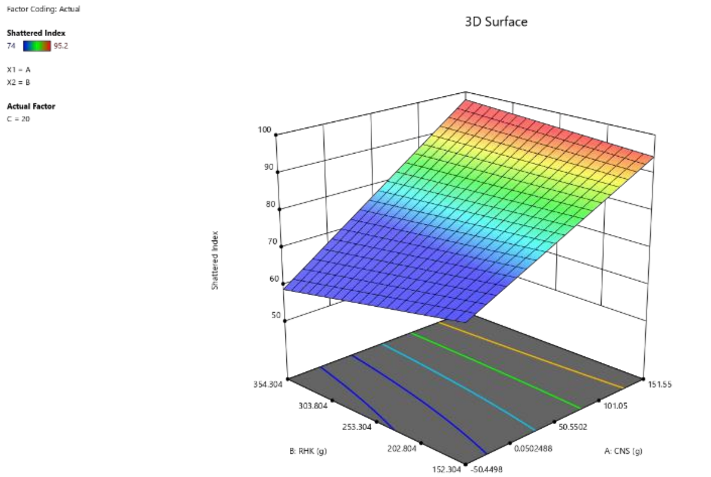

Figure 13: 3D Surface Response of Effect of Mixing Proportions & Binder on Shattered Index of FBCS

Shattered Index =+88.03 +10.88A +0.0000B +0.0000C +3.43AB +0.0000AC + 0.0000BC +0.0000A^2 + 0.0000B^2 + 0.0000C^2 (3)

The constant term 88.03 is the predicted shatter index at the center point of the experimental design space when all coded variables (CNS = A, RHK = B, and dwelling time = C) are set to zero. It serves as the base value from which all other effects are measured. The coefficient +10.88A indicates that an increase in CNS content significantly improves the shatter index. This suggests that coconut shell (CNS) plays a dominant role in enhancing the mechanical integrity and resistance to breakage of the briquettes, likely due to its high lignin and carbon content. Similar observations were reported by [36], who demonstrated that coconut-shell-based briquettes possessed superior impact resistance compared to other agricultural residues due to their higher fixed carbon and lignin-derived binding behaviour. The coefficients 0.0000B (RHK) and 0.0000C (dwelling time) imply that, within the studied range, RHK content and dwelling time have no statistically significant individual effects on shatter index. Although RHK contributes to overall mass, its low bonding potential limits its role in structural reinforcement when used independently. The interaction term +3.43AB suggests a slight synergistic effect between CNS and RHK, potentially due to improved packing. The absence of significant interaction or quadratic terms further confirms that CNS is the dominant factor driving briquette robustness within this formulation window.

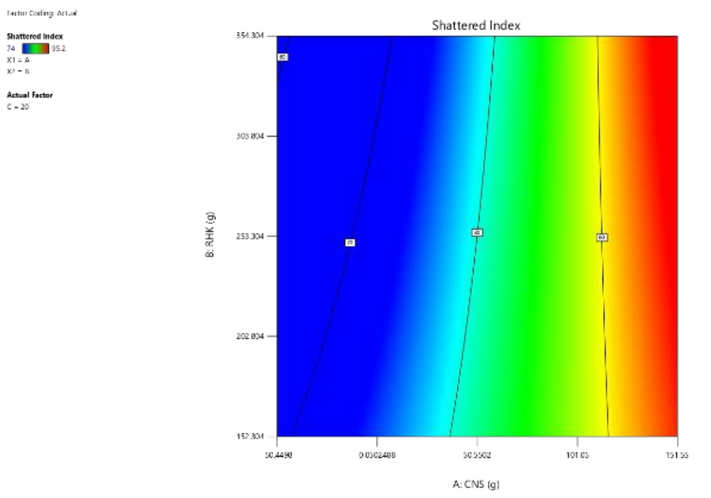

Figure 14: Contour Plot of Effect of Mixing Proportions & Binder on Shattered Index of FBCS

ANOVA for Quadratic Model

The Model F-value of 389.45 implies that the quadratic model for shatter index is statistically significant, with only a 0.26% probability that such a high F-value could occur due to random noise (Table 8). P-values below 0.05 indicate significant model terms, and in this case, factor A (CNS) and the interaction term AB (CNS × RHK) are significant, while other factors and quadratic terms are non-significant or aliased. Insignificant terms may be considered for model reduction if they are not needed to maintain hierarchy.

Table 8: ANOVA for Quadratic model (Aliased)

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	306.22	2	153.11	389.45	0.0026	significant
A-CNS	295.94	1	295.94	752.74	0.0013	
B-RHK	0.0000	0				
C-Dwelling Time	0.0000	0				
AB	10.29	1	10.29	26.16	0.0362	
AC	0.0000	0				
BC	0.0000	0				
A^2	0.0000	0				
B^2	0.0000	0				
C^2	0.0000	0				
Residual	0.7863	2	0.3931			
Cor Total	307.01	4				

Fit Statistics Summary

The statistical analysis of different regression models for shatter index (Table 9) reveals that the "Mean" model is highly significant with a sequential p-value of <0.0001, while the linear model also shows significance (p = 0.0029) and a high lack-of-fit p-value of 0.9519, indicating a good fit and explaining approximately 84.75% of the variability. The 2FI model, which includes two-factor interactions, demonstrates improved explanatory power with an adjusted R^2 of 0.9557 and excellent lack-of-fit (0.9949), although it remains aliased due to confounding effects in the experimental design [29].

Table 9: Fit statistics for regression models of shatter index

Source	Sequential p-value	Lack of Fit p-value	Adjusted R^2	Predicted R^2	
Mean	**< 0.0001**				**Suggested**
Linear	0.0029		0.9519	0.8475	**Aliased**
2FI	0.0362		0.9949	0.9557	**Aliased**

Recommendation for further research

The development of CNS–RHK briquettes presents an opportunity not merely for incremental improvement in biomass fuel technologies but for redefining how agricultural residues are valued within circular economies. The next phase of research should therefore aim beyond material optimization and pursue system-level innovation. Integrating smart densification techniques, AI-driven process control, and modular briquette production units could enable decentralized manufacturing models that empower rural communities to become energy producers rather than consumers. Furthermore, coupling briquette combustion with low-emission stove technologies or hybrid thermal-electric conversion systems could elevate their role from domestic heating fuels to contributors in distributed power generation. Additionally, in order to improve predictions of ideal process parameters, mechanical performance, and combustion efficiency, future research should integrate machine learning techniques like Artificial Neural Networks (ANNs). This will allow for more precise and flexible optimization beyond traditional experimental designs. A global sustainability roadmap supported by life-cycle carbon accounting, socio-economic impact assessment, and policy integration would accelerate large-scale adoption across developing and industrialized regions alike. With the right technological and institutional support, CNS–RHK briquettes can evolve from an experimental biofuel into a strategic instrument for climate resilience, energy justice, and rural industrialisation.

Conclusion

This study shows that torrefaction, natural binder integration, and statistical process optimization can be used to turn agricultural residues specifically, rice husk (RHK) and coconut shell (CNS) into high-performing, environmentally friendly briquettes. Through the use of molasses as a binder and Response Surface Methodology (RSM) for process parameter optimization, the research finds that CNS is the critical reinforcement phase that greatly enhances both compressive strength and shatter resistance. With a compressive strength of 3.63 MPa and a shatter index of 95.2%, the optimised formulation (100% CNS with 10% molasses) demonstrated exceptional structural integrity appropriate for home heating applications. In addition to improving mechanical performance, this work creates a repeatable framework for producing biofuels at scale. Predictable durability, consistent quality, and increased energy efficiency are made possible by the substitution of statistical modeling for trial-and-error fabrication. The results also show how these briquettes can act as a link between the concepts of the circular economy and sustainable energy access, transforming low-value agricultural residues into household fuels that are mechanically sound, energy-dense, and ecologically friendly. The study emphasises that CNS–RHK briquettes offer a practical, affordable, and scalable solution for resilient renewable energy systems when optimized through methodical experimental design. Future research should concentrate on system-level innovations, such as integration with hybrid energy systems or low-emission stove technologies, decentralized production units, and densification procedures aided by AI. By precisely predicting ideal process parameters beyond the current experimental design, Artificial Adaptive Neural Networks (AANNs) optimization of briquette formulations could further enhance mechanical performance and combustion efficiency. In order to ensure that these bio-briquettes not only enhance domestic energy access but also significantly contribute to climate resilience, energy equity, and rural industrialization, life-cycle assessment, socioeconomic evaluation, and policy integration will be essential for widespread adoption. In summary, by integrating material science, process engineering, and sustainability principles, this research advances biomass valorization and shows a feasible way to convert agricultural residues into high-performance, low-emission household fuels that support global clean energy and circular economy goals.

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