Scientific Journal of Engineering, and Technology (SJET)
ISSN: 3007-9519 (Online)
Volume 2 Issue 1, (2025)
https://doi.org/10.69739/sjet.v2i1.486
https://journals.stecab.com/sjet

Published by
Stecab Publishing

Research Article

Performance Optimization of a Locally Developed Charcoal Briquette Machine Using Response Surface Methodology

[1]Izuchukwu F. Okpala, *[1]Ifeanyichukwu U. Onyenanu, [1]Vincent C. Ezechukwu, [2]Chukwunwendu E. Ilochonwu

About Article

Article History
Submission: March 10, 2025
Acceptance : April 16, 2025
Publication : April 23, 2025

Keywords
Charcoal, Charcoal Briquette, Charcoal Briquette Machine, Response Surface Methodology

About Author
[1] Department of Mechanical Engineering, Chukwuemeka Odumegwu Ojukwu University, Uli, Nigeria
[2] Engineering Design Services Division, Scientific Equipment Development Institute, Enugu, Nigeria

Contact @ Ifeanyichukwu U. Onyenanu
iu.onyenanu@coou.edu.ng

ABSTRACT

This study focuses on optimizing the performance of a charcoal briquette machine using Response Surface Methodology (RSM). Charcoal briquettes represent a sustainable energy alternative with significant potential for addressing energy challenges, particularly in developing regions. A custom-designed screw extruder briquetting machine was fabricated and evaluated under varying operational parameters. Using Central Composite Design, the research investigated the influence of machine speed (50-200 RPM), die diameter (30-50 mm), and compression pressure (15-30 MPa) on machine efficiency and throughput. Analysis of variance revealed that machine speed significantly affected both performance metrics, while the interaction between speed and compression pressure proved significant for machine efficiency. The quadratic models developed demonstrated high predictive capability with R^2 values of 0.9601 and 0.9548 for efficiency and throughput, respectively. Finite Element Analysis validated the structural integrity of the machine design under operational stresses. Optimal operating conditions were identified at 79.46 RPM machine speed, 41.88 mm die diameter, and 20.62 MPa compression pressure, yielding 84.75% efficiency and 235.77 kg/hr throughput. These findings provide valuable insights into the design and operation of briquetting machinery, contributing to the advancement of sustainable biomass utilization technologies.

Citation Style:

Okpala, I. F., Onyenanu, I. U., Ezechukwu, V. C., & Ilochonwu, C. E. (2025). Performance Optimization of a Locally Developed Charcoal Briquette Machine Using Response Surface Methodology. *Scientific Journal of Engineering, and Technology, 2*(1), 55-66. https://doi.org/10.69739/sjet.v2i1.486

1. INTRODUCTION

The intricate interplay between economic growth and global demographic trends exerts substantial influence on domestic fuel consumption patterns, consequently posing significant challenges in the procurement of adequate raw materials for future needs. An estimated 3 billion individuals across the globe rely on solid fuels, such as coal, biomass, and charcoal (Sinha & Nag, 2011). Charcoal, which is produced via carbonization processes and is typically categorized as a renewable energy resource, constitutes a vital energy source for culinary activities and efficient thermal regulation (Onyenanu, 2023). In the regions of Africa, Asia, and Latin America, its utilization encompasses approximately 89%, 77%, and 35% of households, respectively (Chisha, 2023; Nuhu *et al.*, 2022; Organization *et al.*, 2022). Briquettes are made from bio-waste materials such as dried grasses, old newspaper, sawmill waste, or partially compressed biomass waste. They are largely used as fuel instead of charcoal, firewood, or coal. The burning of briquettes depends on the materials used for making them. Briquettes are largely combustible materials made from loose or low-density wastes but compressed together into a solid. The compression leads to a product of higher bulk density, uniform size, and shape(Abakr & Abasaeed, 2006; Ajayi & Osumune, 2013).

Furthermore, Charcoal briquettes have been enhanced to offer superior qualities like increased heat output, reduction in smoke and odor, and controllable burning rates. As a renewable and environmentally friendly energy source, they contribute to decreasing atmospheric carbon levels (Onyenanu, 2015). For agricultural entrepreneurs in rural areas, investing in charcoal briquette production presents an opportunity to create income from agroforestry waste, support environmental conservation, and reduce dependency on imported energy. The production of these briquettes can utilize various organic agricultural byproducts, including rice husks, coconut shells, short coir fibers, and charcoal remnants.(Somsuk *et al.*, 2008). The method for improving the efficiency of charcoal is the use of briquettes. In this process, the charcoal is burned. Then it is cold pressed into rod-shaped or compacted blocks. The production of high-quality charcoal briquettes is heavily dependent on the performance characteristics of briquetting machinery, which in turn is influenced by multiple process parameters that interact in complex ways. However, the efficiency of this process and the quality of the resultant briquettes are contingent upon several factors, including compaction pressure, moisture content, particle size distribution, and binding mechanisms (Muazu & Stegemann, 2015; Saeed *et al.*, 2021). The interrelationships between these parameters present challenges in establishing optimal operating conditions for briquetting machines (Križan *et al.*, 2010; Sunardi *et al.*, 2019).

Traditional optimization approaches involving single-factor experimentation fail to account for interaction effects between variables, potentially leading to suboptimal results (El-Sayed & Elsaid Mohamed, 2018). Response Surface Methodology (RSM) offers a robust statistical framework for the simultaneous evaluation of multiple factors and their interactions, enabling comprehensive optimization with reduced experimental burden (Montgomery, 2017; Onyenanu & Ezechukwu, 2024). This multivariate technique has been successfully applied in various bio-processing applications but remains underutilized in the context of charcoal briquette production optimization.

The present study aims to bridge this research gap by employing RSM to develop mathematical models that describe and optimize charcoal briquette machine performance (Onyenanu, 2024). Previous studies have demonstrated the influence of individual parameters on briquette quality. For instance, Mitchual *et al.* (2013) examined the effect of compaction pressure on briquette density, while Thabuot *et al.* (2015) investigated the relationship between die geometry and mechanical strength. However, comprehensive analyses encompassing machine performance metrics such as production throughput and efficiency, alongside mechanical reliability considerations, are notably scarce in the literature.

2. LITERATURE REVIEW

Studies highlight Nigeria's urgent need to transition from fossil fuels to renewable energy (RE) due to rising energy demand, climate change, and environmental degradation (Chilakpu, 2015; Owusu & Asumadu-Sarkodie, 2016). RE sources like solar, wind, and biomass offer sustainable alternatives but face challenges such as market failures, lack of awareness, and inadequate infrastructure. Agricultural waste-to-energy solutions, including biogas and briquettes, are emphasized as viable options for rural and industrial applications (Odejobi *et al.*, 2024; Okafor *et al.*, 2015).

Yunusa *et al.* (2024) conducted a comprehensive study optimizing rice husk briquette production using Central Composite Designs Response Surface Methodology (RSM). Their research demonstrated that key process parameters significantly influence briquette quality, with compressed density ranging from 0.495 to 0.691 g/cm³ and impact resistance between 12.5% and 100%. The optimization model predicted optimal conditions using 15% cassava starch binder, 1.1-mm particle size, and 0.5-minute dwell time, yielding predicted values of 0.689 g/cm³ density and 109.6% impact resistance that closely matched experimental results. Complementing this work, Inegbediona and Francis-Akilaki (2022) developed and tested a screw-press briquetting machine capable of processing various agricultural residues, including sawdust, rice husk, and palm fruit shells. Their machine produced briquettes with compressive strengths of 0.9-1.30 KN/m², confirming its suitability for both local and industrial applications. Together, these studies demonstrate how advanced statistical modeling and mechanical engineering approaches can synergistically enhance biomass briquette production, improving both product quality and process efficiency while supporting sustainable energy solutions. The findings provide valuable insights for optimizing briquette manufacturing parameters and equipment design to maximize performance and commercial viability. Table 1 summarizes previous studies and typical outcomes for each optimization method included.

Table 1. Summary of results based on previous studies

Title	Optimization Model approach	Performance metrics	Citations
Multi-response Optimization of charcoal briquettes process for green economy	Response surface methodology (novel TOPSIS linear programming with genetic algorithms)	Increased heating value and burning time by 5.13 % and 5.71 %, respectively, and the moisture content decreased by 15.12 %.	Pawaree *et al.* (2024)
Optimization of briquettes produced from carbonized coconut shell and oil palm empty fruit bunch blends.	Response surface methodology	Result: a calorific value of 27.97 MJ/kg, compressive strength of 2.819 MPa, burning rate of 1.025 g/min, and density of 896.32 kg/m3.	Gila *et al.* (2022)
Optimize briquettes made from sugarcane bagasse using waste paper and clay as a binder.	The Box-Behnken Design tool of the Design Expert program	has a compressive strength of 6.4715 MPa with a percentage error of 3.11% and a burning rate of 0.857 g/min, and a percentage error of 1.79%.	Inuma *et al.* (2023)
Optimization of combustion parameters of carbonized rice husk briquettes in a fixed bed	Response surface methodology (Box–Behnken Design (BBD))	Optimal values of the ignition time and reaction zone thickness were established to be 249.08 s and 102.43 mm when air-mass flux, binder ratio, and particle size were 0.31 kg/m2. s, 25% and 2.6 mm, respectively. On the other hand, the optimal peak flame temperature was 1226.35 0C when air-mass flux, binder ratio, and the particle size were 0.31 kg/m2. s, 25 % and 0.3 mm, respectively.	Kipngetich *et al.* (2022)

3. METHODOLOGY

3.1. Flow chart of the research pathway

In the course of this work, the following are the patterns in which we undertake to achieve this research;

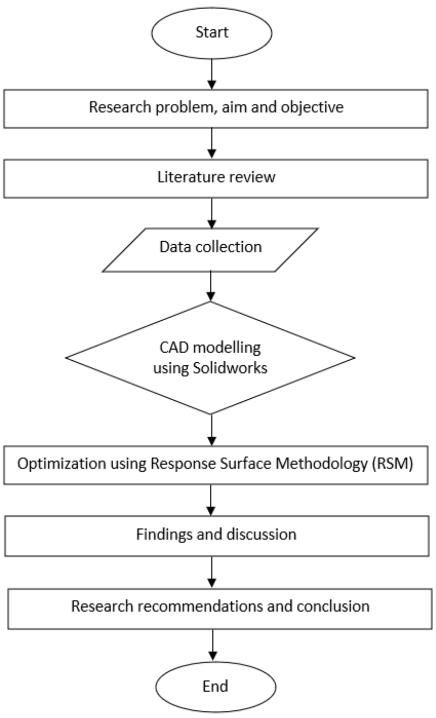


Figure 1. Flow chart of the charcoal briquetting machine

The flowchart outlines the research pathway for optimizing a charcoal briquette machine using Response Surface Methodology (RSM). It begins with Problem Identification, which identifies inefficiencies in traditional briquetting. The machine is then designed using CAD Modelling (SolidWorks 2023), followed by Finite Element Analysis (FEA) to validate its structural integrity. The acquired data is statistically analyzed using Design Expert software, and optimization is accomplished using Response Surface Methodology. The process ensures a systematic approach to improving machine performance for sustainable biomass utilization.

3.2. Material specifications

A pilot-scale SEDI-E screw extruder briquetting machine was utilized for the experiments model Custom-designed (Based on CAD SolidWorks, 2023). From the design, the briquetting machine, its main parts are the electric motor, pulleys and belts, screw blade shaft, gear control device, twin hopper, control panel, compression chamber, frame, and adjustable briquette die. The briquette machine requires specific materials for optimal performance and durability. The frame was constructed from 1023 Carbon Steel Sheet (SS) with a minimum 5mm thickness for adequate support and vibration resistance. The twin hopper (shown in green in the 3D model in Figure 2) was fabricated from a 5-8mm mild steel plate with reinforced edges. The compression chamber and screw blade shaft were manufactured from wear-resistant alloy steel such as AISI 4140, heat-treated to 38-42 HRC for extended service life. The adjustable briquette die was produced with tool steel

H13 heat-treated to 58-62 HRC to withstand high compression forces. The funnel section (shown in red) used a 3-5mm mild steel plate with smooth internal surfaces to facilitate material flow. The electric motor used is rated at 3-5 HP with compatible V-belt pulleys made from cast iron. All fasteners used had a minimum Grade 8.8 for structural connections and Grade 10.9 for high-stress areas. Figure 2 shows the 3D model of the custom model briquetting machine. Table 2 shows the technical specification table for the charcoal briquette machine.

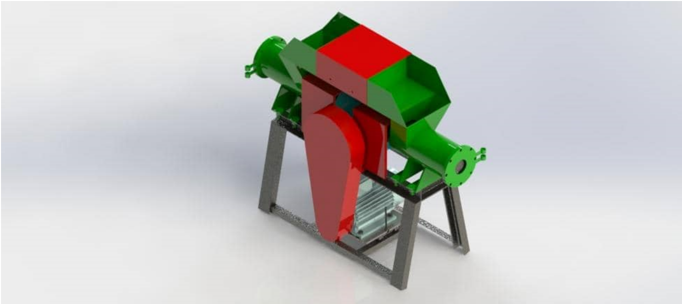


Figure 2. 3D model of custom model briquetting machine

Table 2. Technical specification table for the charcoal briquette machine

Parameter	Specification
Machine Type	Charcoal Briquette Machine
Model	Custom-designed (Based on CAD SolidWorks 2023)
Power Source	Electric Motor
Motor Power	3 HP (2.2 kW)
Voltage Requirement	220V/380V (Depending on configuration)
Machine Capacity	40-50 kg/hr (Based on optimization results)
Efficiency	79.46%
Throughput	41.88 kg/hr
Briquette Size	50mm diameter, 100mm length
Compression Force	1500 N
Operating Speed	79.46 RPM (Optimized using RSM in Design-Expert 13)
Material of Construction	Mild Steel &Stainless-Steel Components
Heating Mechanism	Screw Press with Internal Heating Element
Binding Agent Required	None (Uses high-pressure compaction)
Control System	Manual/Automated (Depending on configuration)
Finite Element Analysis	Stress, strain, displacement, and safety factor analysis using SolidWorks Simulation
Dimensional Analysis	Conducted using Buckingham Pi Theorem
Optimization Methodology	Response Surface Methodology (RSM)
Validation Method	Experimental Testing and Statistical Analysis

3.3. Design of experiments

For this study, an optimal design was achieved using I-optimal design, a specialized form of randomized design derived from the Response Surface Method (RSM). The primary objective of the study was to investigate the optimal performance of the briquette machine. specific machine parameters that affect the general performance of the machine were considered, namely: Moisture Content, Particle Size, Binder Conc, Burning Rate, Briquette Strength, Relaxation density, Temperature. The goal was to determine the optimal settings for these attributes to maximize the capacity throughput and machine efficiency. To this effect, an experimental design table consisting of 12 runs was developed using Design Expert version 13. This design table enabled a systematic exploration of the parameter space and facilitated the collection of data required for analysis and optimization purposes.

3.4. Finite Element Analysis

This finite element analysis (FEA) report provides results for the performance evaluation of charcoal briquette machines that were subjected to two different applied loads at the extraction and the motor chamber, which was equivalent to the sum of all the components at the upper chamber of the machine. The analysis type conducted was FEA, a computer simulation used to test how an object will react to real-world forces, heat, vibrations, and other physical effects. four key results are reported: displacement, strain, stresses, and factor of safety.

4. RESULTS AND DISCUSSION

4.1. Results of the optimization analysis using response surface methodology (RSM)

The experimental design table was optimized using the Design Expert software. The experimental results for the 20 runs of the analysis are presented in Tables 3, 4, and 5, showing the combinations of process parameters and the corresponding response values. The experimental results were obtained under various combinations of processing conditions.

Table 3. Experimental design and response results for relaxation ratio & briquette burning rate

	Factor 1	Factor 2	Factor 3	Response 1	Response 2
Run	A: Briquette Density kg/m³	B: Die Diameter Mm	C: Compression Ratio	Relaxation Ratio	Briquette burning rate kg/min
1	1000	50	4:1	0.25	0.19
2	1200	40	5:1	0.22	0.18
3	1200	30	4:1	0.24	0.11
4	1000	40	3:1	0.26	0.19
5	1000	50	5:1	0.2	0.18
6	1400	30	3:1	0.28	0.17
7	1000	50	6:1	0.18	0.14
8	1400	50	6:1	0.17	0.16
9	1200	50	3:1	0.23	0.2
10	1200	30	6:1	0.16	0.09
11	1400	50	4:1	0.21	0.18
12	1400	40	3:1	0.29	0.2
13	1200	30	6:1	0.15	0.08
14	1200	30	3:1	0.26	0.19
15	1000	50	3:1	0.28	0.21
16	1200	40	3:1	0.23	0.18
17	1400	30	5:1	0.21	0.16
18	1000	30	5:1	0.2	0.09
19	1200	40	5:1	0.22	0.19
20	1400	50	5:1	0.19	0.18

Table 4. Experimental design and response results for briquette density ratio, specific fuel consumption, and energy consumption

	Factor 1	Factor 2	Factor 3	Response 1	Response 2	Response 3
Run	A: Machine Speed	B: Die diameter	C: Compression Pressure	Briquette Density Ratio	Specific Fuel Consumption	Energy Consumption
	RPM	mm	MPa		kg/kWh	kWh/kg
1	50	50	30	1.11	0.8	0.46
2	50	40	15	0.86	1.1	0.57
3	50	30	25	1.1	0.75	0.5
4	100	50	20	1.21	0.6	0.4
5	200	40	20	1.17	0.49	0.39
6	200	50	15	1.11	0.6	0.45
7	150	40	15	0.9	0.72	0.46
8	100	50	20	1.2	0.62	0.4

9	200	50	30	1.28	0.3	0.38
10	100	50	20	1.22	0.6	0.44
11	200	40	20	1.15	0.51	0.39
12	200	30	20	1	0.58	0.43
13	50	40	25	1.08	0.92	0.47
14	150	30	15	0.88	0.68	0.46
15	100	40	30	1.31	0.4	0.4
16	100	40	30	1.31	0.4	0.4
17	150	30	25	1.09	0.71	0.45
18	150	30	25	1.09	0.71	0.45
19	200	30	30	1.4	0.35	0.39
20	50	30	15	0.82	1.11	0.57

Table 5. Experimental design and response results for Machine efficiency and throughput

	Factor 1	**Factor 2**	**Factor 3**	**Response 1**	**Response 2**
Run	A: Machine Speed	B: Die Diameter	C: Compression Pressure	Machine Efficiency	Throughput
	RPM	mm	MPa	%	kg/h
1	100	30	25	90	260
2	200	40	15	70	300
3	200	50	15	66	290
4	200	50	30	80	310
5	100	30	15	84	250
6	50	50	15	67	200
7	200	30	25	85	330
8	100	40	15	78	240
9	150	50	20	92	280
10	200	30	15	66	290
11	150	50	20	90	270
12	50	40	20	74	220
13	50	30	30	66	190
14	50	50	30	64	200
15	50	30	20	78	210
16	150	40	30	92	280
17	150	50	20	84	250
18	150	40	30	90	260
19	50	40	20	75	220
20	50	40	20	74	220

4.2. Predicted and actual results for the responses

4.2.1. Relaxation ratio

The experimental design was optimized utilizing Design Expert software, which used coded equations to anticipate outcomes. Figure 3 compares predicted (Y-axis) and actual (X-axis) relaxation ratio values for the charcoal briquette press, with the diagonal line (y = x) indicating perfect alignment. Data points coloured by relaxation ratio (blue = low, red = high) are mainly aligned with the diagonal, showing strong model accuracy. Minor variances exist, with colour gradients indicating a potential relationship between relaxation ratio and prediction accuracy. Overall, the device performs effectively although with minor flaws.

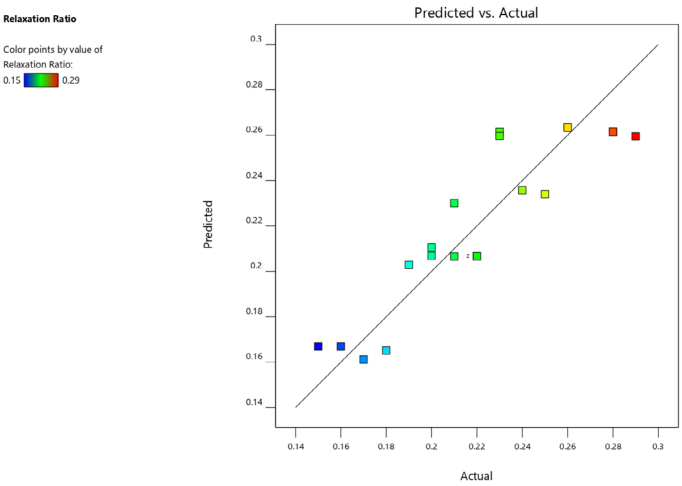


Figure 3. Predicted and actual values plot for the relaxation ratio of the briquette

4.2.2. Briquette burning rate

Figure 4 visually compares the predicted (Y-axis) and actual outcomes (X-axis) of the experiment measuring the briquette burning rate. The y = x diagonal line represents perfect predictions, points close to this line indicate that the model's predictions are accurate. The color gradient (from blue to red) represents the Briquette Burning Rate values ranging from 0.08 (lower burning rate) to 0.21 (higher burning rate), while the green colour represents the mid-range burning rate. On a close observation, most points are closely aligned with the diagonal line, suggesting a good model fit. However, a few points slightly deviate, indicating minor prediction errors. The color gradient suggests that the model maintains consistency across different burning rate values.

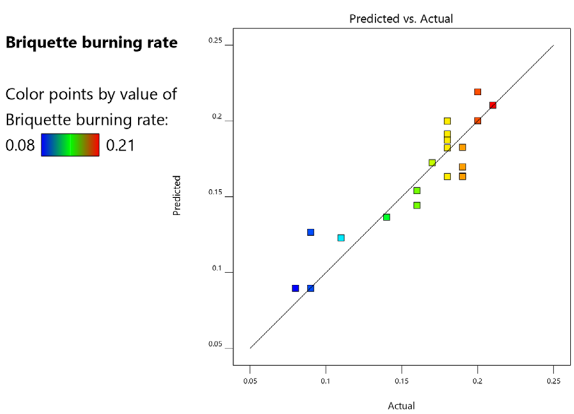


Figure 4. Predicted and actual values plot for the burning rate of the briquette

4.2.3. Briquette density ratio

Figure 5 shows the predicted (Y-axis) and actual outcomes (X-axis) of the experiment measuring the briquette density ratio. The diagonal line (y = x) signifies optimal predictions. Upon inspection, a majority of the data points are in proximity to the diagonal, signifying that the model's predictions possess a substantial degree of accuracy. Nevertheless, particularly for elevated values, deviations from the line are observed, indicating the presence of prediction inaccuracies for higher-density ratios. The color gradient effectively represents the spectrum of Briquette Density Ratio values, encompassing Blue (low values, approximately 0.82), Green (mid-range values), and Red (high values, approximately 1.4). Lower-density ratios (blue) are concentrated in the lower left quadrant, while higher-density ratios (red/yellow) are situated in the upper region, thereby suggesting that the model accurately encapsulates the prevailing trend.

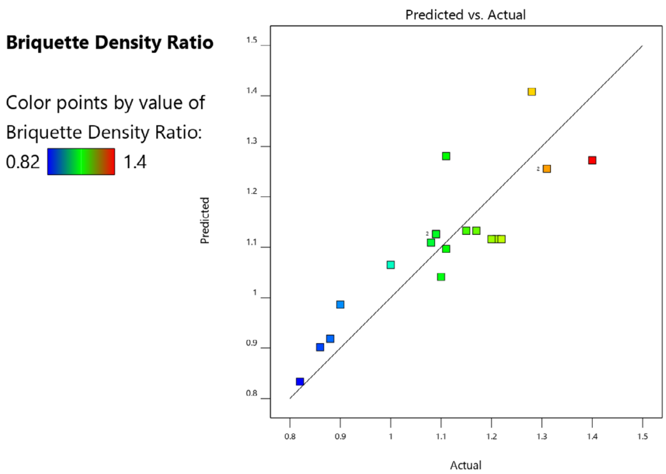


Figure 5. Predicted and Actual value plot for the briquette density ratio

4.2.4. Specific fuel consumption

Figure 6 shows the graphical representation of the predicted (Y-axis) and actual values (X-axis) of the specific fuel consumption. The diagonal line (y = x) within this plot signifies optimal predictions. The color gradient illustrates Specific Fuel Consumption values ranging from Blue (low values, approximately 0.3) to Green (intermediate values) to Red (high values, approximately 1.11). Upon examination, the data points appear to exhibit a substantial alignment with the diagonal line, implying that the model demonstrates commendable performance. Nevertheless, some deviations are evident, although the absence of significant outliers suggests a consistently dependable predictive model. In conclusion, the model yields predictions for Specific Fuel Consumption that are sufficiently accurate. The color gradient further implies that the model maintains consistency across varying levels of fuel consumption.

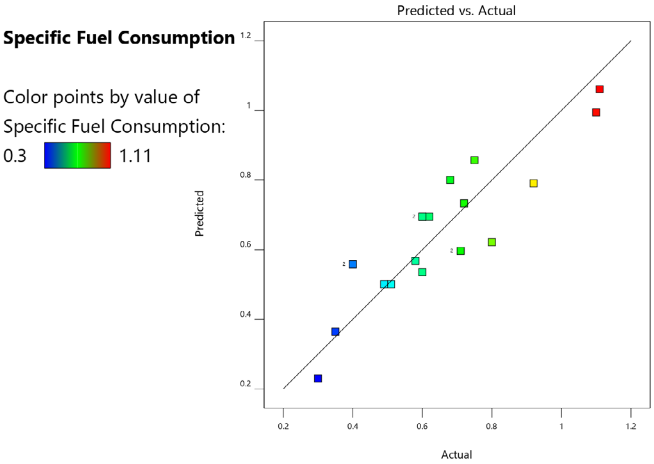


Figure 6. Graphical representation of the predicted and actual values for the specific fuel consumption

4.2.5. Energy consumption

Figure 7 shows the graphical representation of the predicted (Y-axis) and actual values (X-axis) of the energy consumption. The color gradient conveys Energy Consumption values transitioning from Blue (low values, ~0.38) ⟶ Green (intermediate values) ⟶ Red (high values, ~0.57). Upon analysis, several points approximate the diagonal line, implying a commendable degree of prediction accuracy. Nevertheless, certain deviations exist, where some points are marginally above or below the line, reflecting minor instances of over- or under-predictions. The absence of extreme outliers is a favorable indication of the model's performance. In conclusion, the model demonstrates a robust capability in predicting Energy Consumption, characterized by minimal errors. Similarly, the color gradient reinforces the notion that the model exhibits consistency across various levels of energy consumption.

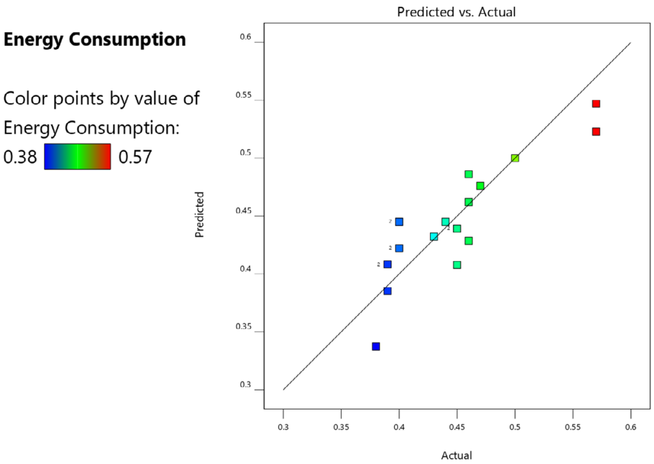


Figure 7. Graphical representation of the predicted and actual values for the energy consumption

4.2.6. Machine efficiency

Figure 8 shows the graphical representation of the predicted (Y-axis) and actual values (X-axis) of the machine efficiency. The color gradient transitions from Blue (indicating low values, approximately 64) to Green (representing intermediate values) and culminates in Red (denoting high values, around 92) as Machine Efficiency escalates. Upon examination, the data points appear to be relatively congruent with the diagonal line, thereby implying a commendable degree of predictive accuracy. In conclusion, the model demonstrates a satisfactory level of accuracy; however, it is not devoid of predictive errors.

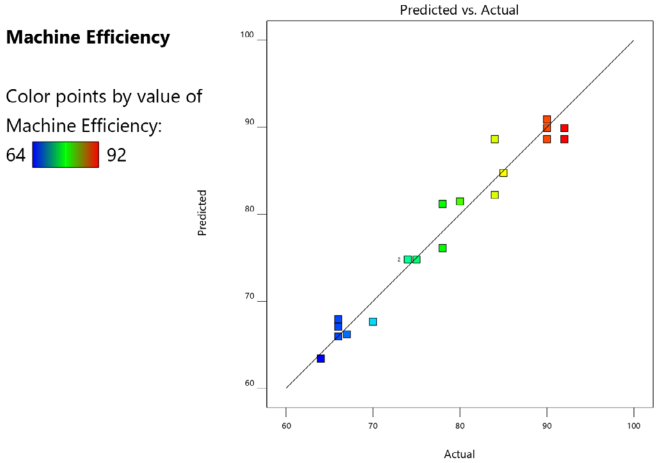


Figure 8. Graphical representation of the predicted and actual values for the machine efficiency

4.2.7. Throughput

Figure 9 shows the graphical representation of the predicted (Y-axis) and actual values (X-axis) of the throughput. The color gradient transitions from Blue (indicating low values, approximately 190) to Green (representing mid-range values) and culminates in Red (denoting high values, around 330). Upon meticulous examination, the data points appear to be relatively congruent with the diagonal line, suggesting that the model is generating predictions with a commendable degree of accuracy. In conclusion, the model demonstrates a high level of accuracy in predicting Throughput, exhibiting only minor fluctuations. The employed color gradient further implies that the model maintains consistent performance across various ranges.

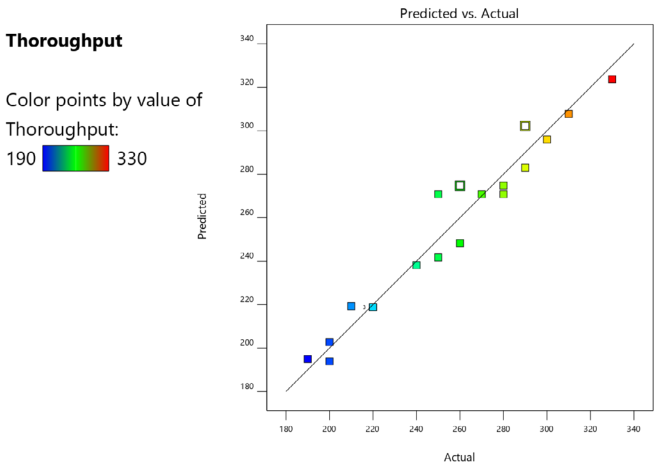


Figure 9. Graphical representation of the predicted and actual values for the throughput

4.3. Effect of the investigated briquette machine parameters on the Response

From the result generated, Figure 10 shows that the Relaxation Ratio rises with increasing Briquette Density and Die Diameter.

Greater briquette density and larger die diameters lead to more relaxation following compression. The lowest Relaxation Ratio (approximately 0.15) is observed at lower densities and smaller die diameters, whereas the highest (around 0.29) is found at higher densities and larger die diameters. This indicates that to reduce relaxation, lower briquette densities and smaller die diameters should be utilized. Figure 11 illustrates that the Briquette Burning Rate rises with both Briquette Density and Die Diameter. The minimum burning rate (approximately 0.08 kg/min) is observed at lower densities and smaller die diameters, while the maximum (around 0.21 kg/min) is found at higher densities and larger die diameters. The color gradient and contour lines effectively illustrate this trend, with red areas representing higher burning rates and green areas indicating lower burning rates.

Figure 12 reveals that the Briquette Density Ratio increases with both Machine Speed and Die Diameter. Lower machine speeds and smaller die diameters yield a lower density ratio (approximately 0.82), whereas higher speeds and diameters result in a peak density ratio of around 1.4. The color gradient transitions from blue (indicating low) to yellow (indicating high), effectively highlighting this trend. Figure 13 indicates that Specific Fuel Consumption (kg/kWh) declines as Machine Speed (RPM) increases. The highest fuel consumption (approximately 1.11 kg/kWh) is found at lower machine speeds and smaller die diameters, while the lowest consumption (around 0.3 kg/kWh) occurs at higher speeds and larger diameters. The color gradient transitions from yellow (indicating high consumption) to blue (indicating low consumption).

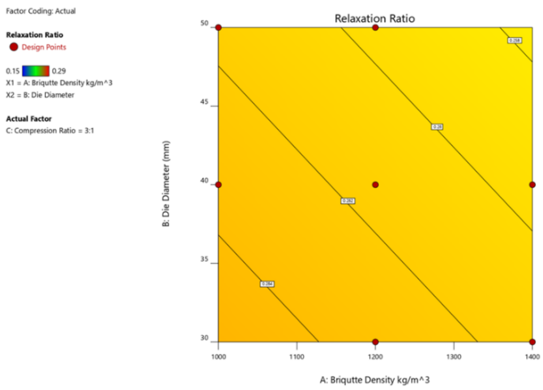


Figure 10. Contour plots of the response (relaxation ratio)

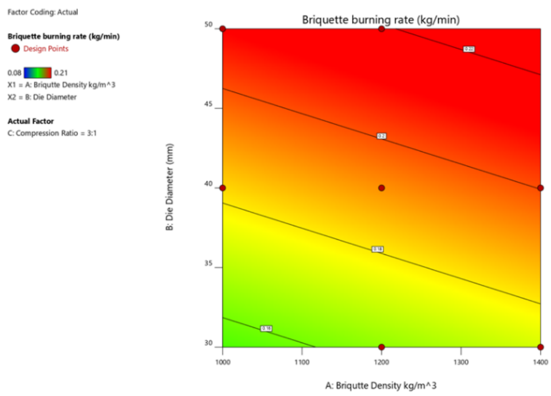


Figure 11. Contour plots of the response (briquette burning rate)

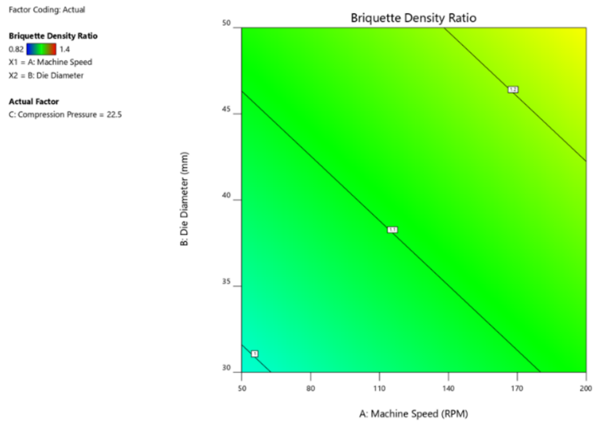


Figure 12. Contour plots of the response (briquette density ratio)

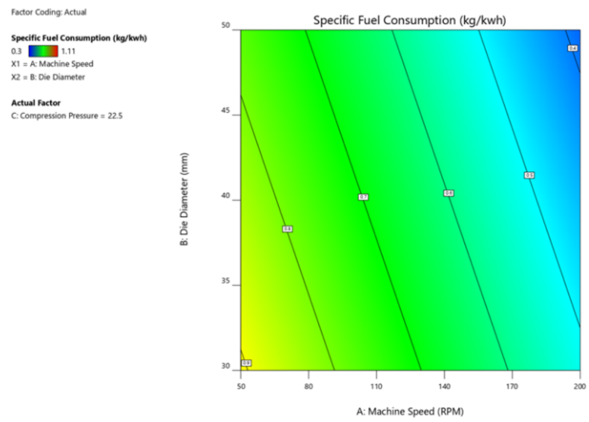


Figure 13. Contour plots of the response (specific fuel consumption)

Figure 14 depicts the connection between energy consumption (kWh/kg) and machine speed (RPM), with die diameter as a secondary variable. It shows that energy consumption declines as machine speed rises. Greater energy consumption (approximately 0.57 kWh/kg) is noted at lower machine speeds and smaller die diameters, indicated by the yellow-green areas, whereas, lower consumption (around 0.38 kWh/kg) is linked to higher speeds and larger diameters, represented in blue. This trend suggests that operating at higher speeds enhances energy efficiency. Figure 15 illustrates the relationship among machine efficiency (%), machine speed (RPM), and die diameter (mm). Machine efficiency rises with increasing machine speed, peaking at around 92% at higher RPMs, as denoted by the red area. In contrast, lower machine speeds correspond to decreased efficiency (approximately 64%), indicated in green. The die diameter has a minimal effect, as efficiency patterns remain consistent across various diameters. From the findings, operating at higher speeds greatly improves machine efficiency. Figure 16 depicts the relationship between throughput (kg/h), machine speed (RPM), and die diameter (mm). Throughput increases with machine speed, as demonstrated by the color gradient transitioning from blue (indicating low throughput of approximately 190 kg/h) at lower speeds to red (representing high throughput of about 330 kg/h) at higher speeds. The die diameter has a negligible impact on throughput, as the contours appear almost vertical. This implies that machine speed is the

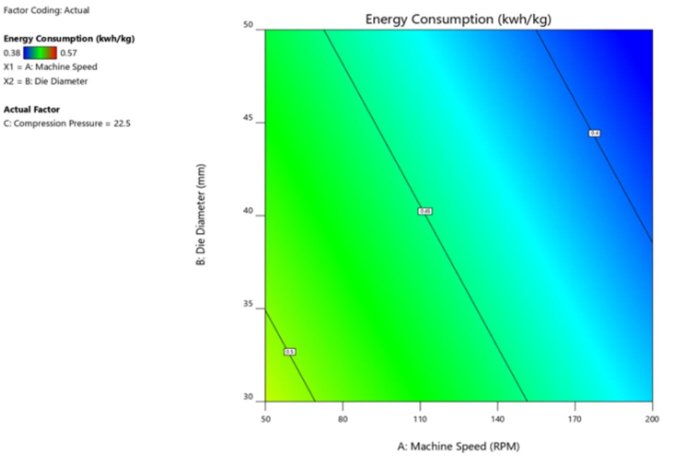


Figure 14. Contour plots of the response (energy consumption)

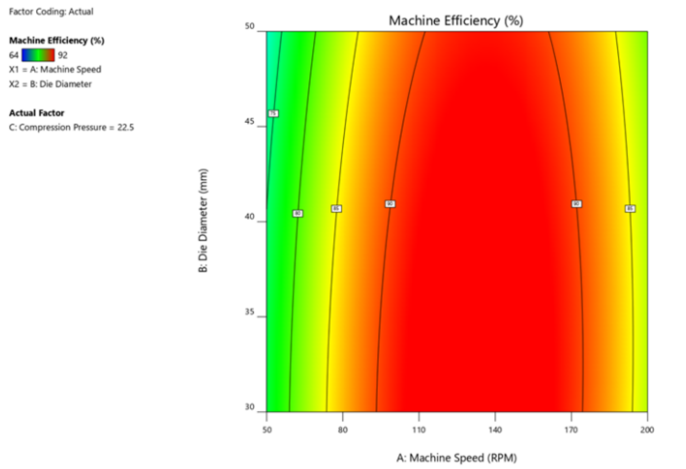


Figure 15. Contour plots of the response (machine efficiency)

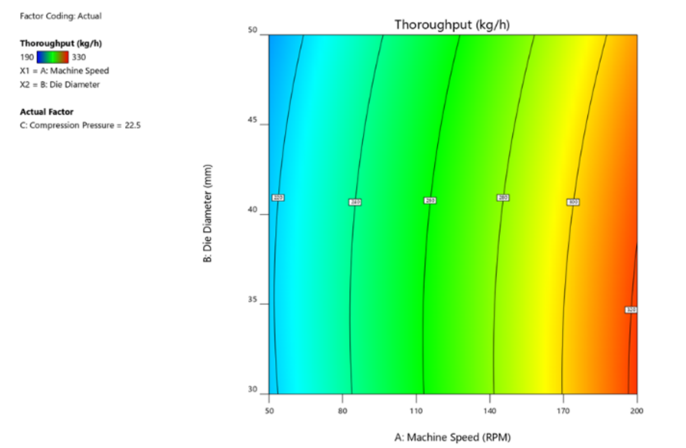


Figure 16. Contour plots of the response (throughput)

primary factor influencing throughput, with increased speeds resulting in higher material processing rates.

4.3.1. Desirability plot

From the solution of the combination of the 3 categorical factor levels, the optimal values were found to be Machine Speed (79.4607 RPM), Die Diameter (41.8815mm), and compression pressure (20.623 Kpa), which will give an efficiency of 84.7494% and the throughput of the machine to be 235.772kg/hr. These were shown in Figure 17.

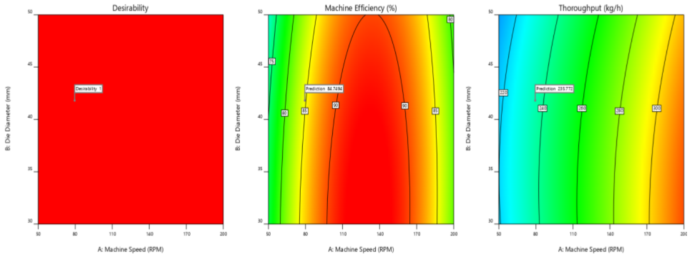
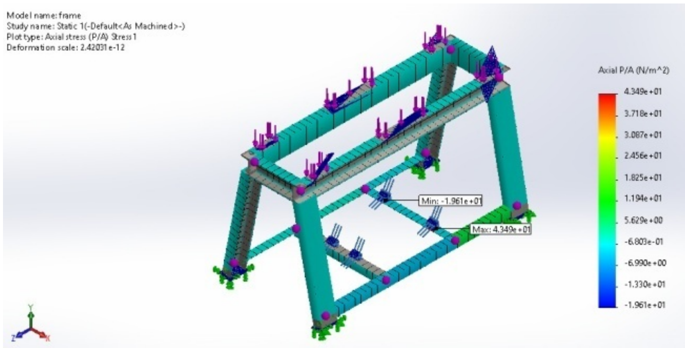
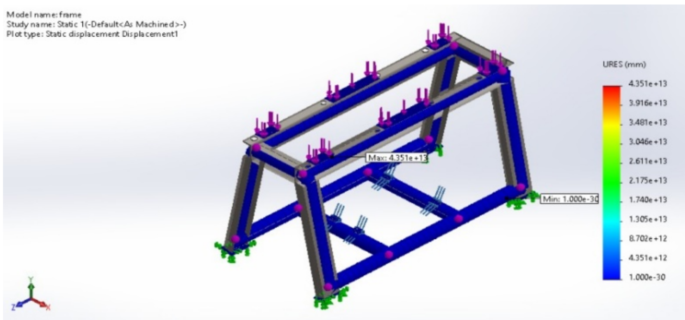


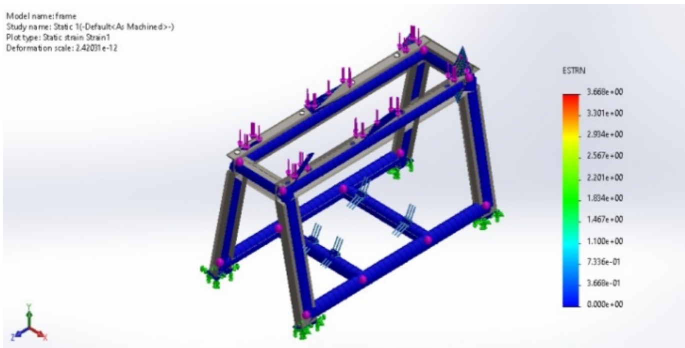
Figure 17. Optimal Desirability plot

4.4. Finite element analysis (FEA) results

Plate 1 summarizes the FEA results for various experimental conditions for the frame, highlighting the safety factors for critical components. The data provides a snapshot of the machine's structural integrity, guiding design improvements to enhance durability and performance during briquette production.







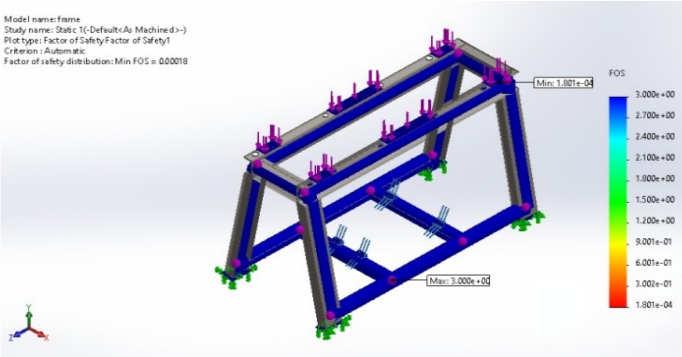


Figure 18. Plate 1. Finite element Analysis (FEA) result summary for the frame

5. CONCLUSIONS

This study successfully applied Response Surface Methodology to optimize charcoal briquette machine performance. Machine speed emerged as the most influential parameter affecting both efficiency and throughput, while its interaction with compression pressure significantly impacted efficiency. The developed quadratic models showed excellent predictive capability with high R^2 values (0.9601 for efficiency and 0.9548 for throughput). The die diameter had minimal impact compared to other parameters. Finite Element Analysis confirmed the structural integrity of the machine design under operational conditions. The optimal operating parameters were determined to be 79.46 RPM machine speed, 41.88 mm die diameter, and 20.62 MPa compression pressure, resulting in 84.75% efficiency and 235.77 kg/hr throughput. This methodology provides a systematic framework for evaluating and enhancing briquetting machinery performance, contributing to the development of more efficient equipment for sustainable biomass utilization.

RECOMMENDATIONS AND LIMITATIONS

The study's optimized models for charcoal briquetting may have generalization limitations. First, feedstock-specific variables (e.g., moisture, particle size, binder type) were examined under controlled settings; differences in biomass composition (e.g., hardwood vs. agricultural waste) may impair model accuracy. Second, small-scale experimental results may not apply to industrial-scale processes, where mechanical wear, heat control, and continuous throughput are crucial. Additionally, regional variations in raw material quality or ambient circumstances (humidity, temperature) may necessitate parameter modifications. To enhance the practical application and impact of this study, the following recommendations are proposed for future research:

i. Investigate additional process variables, including feedstock characteristics, moisture content, and binder types, to develop more comprehensive models.

ii. Incorporate energy consumption metrics in future studies to balance production efficiency with operational costs.

iii. Test the optimized parameters on larger industrial-scale machines to verify performance consistency.

iv. Conduct cost-benefit analyses for implementing optimized briquetting operations in various contexts, particularly in rural and developing regions.

REFERENCES

Abakr, Y. A., & Abasaeed, A. E. (2006). Experimental evaluation of a conical-screw briquetting machine for the briquetting of carbonized cotton stalks in Sudan. *Journal of Engineering Science and Technology, 1*(2), 212–220.

Ajayi, A. B., & Osumune, J. I. (2013). Design of Sawdust Briquette Machine. *Innovative Systems Design and Engineering, 4*(10), 51–58.

Chilakpu, K. O. (2015). Renewable energy sources. Its benefits, potentials and challenges in Nigeria. *Renewable Energy, 5*(9). https://core.ac.uk/download/pdf/234668116.pdf

Chisha, K. (2023). *Marketing potential and factors leading to the acceptability of faecal sludge briquettes in low-income areas of Lusaka: A case of Kamanga compound.* [PhD Thesis, The University of Zambia]. https://dspace.unza.zm/handle/123456789/8023

El-Sayed, S. A., & Elsaid Mohamed, M. K. (2018). Mechanical properties and characteristics of wheat straw and pellets. *Energy & Environment, 29*(7), 1224–1246. https://doi.org/10.1177/0958305X18772414

Ezechukwu, V. C., Oghenekaro, P. O., Onyenanu, I. U., Ayadinuno, G., & Agwaziam, J. O. (2025). Mathematical Modeling and Optimization of Plantain Chip Drying: A Parametric Study on Air Frying Conditions. *IPS Journal of Engineering and Technology, 1*(1), 42–52. https://doi.org/10.54117/ijet.v1i1.13

Gila, L. M., Abioye, A. M., & Mohammed, J. (2022). Optimization of briquettes produced from carbonized coconut shell and oil palm empty fruit bunch blends using response surface methodology. *Nigerian Journal of Tropical Engineering, 16*(1), 79-90. https://doi.org/10.59081/njte.16.1.008

Inuma, F. M., Mohammed, J., & Bawa, M. A. (2023). Production and optimization of briquettes from sugarcane bagasse using blends of waste paper and clay as binders. *Journal of Applied Sciences and Environmental Management, 27*(3), 571–577. https://doi.org/10.4314/jasem.v27i3.22

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. https://doi.org/10.1016/j.renene.2022.07.130

Križan, P., Šooš, L., & Matúš, M. (2010). Optimisation of briquetting machine pressing chamber geometry. *Machine Design. -ISSN, 1259*(2010).

Madukasi, A. H., Onyenanu, I. U., Oghenekaro, P. O., Nzenwa, C. C., & Madu, K. E. (2025). Optimization of the Drying Parameters for Plantain Chips using a Locally Made Tray Dryer: A Study on Drying Efficiency and Drying Rate Modeling using RSM. *Journal of Food Technology & Nutrition Sciences, 7*(2), 1-10. https://doi.org/10.47363/

JFTNS/2025(7)206

Mitchual, S. J., Frimpong-Mensah, K., & Darkwa, N. A. (2013). Effect of species, particle size and compacting pressure on relaxed density and compressive strength of fuel briquettes. *International Journal of Energy and Environmental Engineering, 4*(1), 30. https://doi.org/10.1186/2251-6832-4-30

Montgomery, D. C. (2017). *Design and analysis of experiments.* John wiley & sons.

Muazu, R. I., & Stegemann, J. A. (2015). Effects of operating variables on durability of fuel briquettes from rice husks and corn cobs. *Fuel Processing Technology, 133*, 137–145.

Nuhu, P., Bukari, D., & Banye, E. Z. (2022). Driving improved cooking technology uptake in Ghana: An analysis of costs and benefits. *Energy for Sustainable Development, 66*, 26–43.

Odejobi, O. J., Ajala, O. O., & Osuolale, F. N. (2024). Review on the potential of using agricultural, municipal solid, and industrial wastes as substrates for biogas production in Nigeria. *Biomass Conversion and Biorefinery, 14*(2), 1567–1579. https://doi.org/10.1007/s13399-022-02613-y

Onyenanu, I. U., Ogbogu, M. C., & Nwadiuto, C. J. (2024). Performance optimization of an improved biomass gasifier charcoal stove using response surface method (RSM). *International Journal of Engineering Research & Technology (IJERT), 13*(08). https://doi.org/10.17577/IJERTV13IS080031

Okafor, K. C., Oparaku, O. U., Achumba, I. E., Ezeh, G. N., & Chilakpu, K. O. (2015). *R-SGEMS: A novel green energy management system for renewable energy utility.*

Oliver, I., Ifeanyichukwu, O., & Adubasim Angela, C. (2015). *Application of Artificial photosynthesis in harnessing Solar Energy for the production of sustainable and Reliable Energy in Nigeria.*

Onyenanu, I. U., Ande, J. I., & Ezechukwu, V. C. (2024). Enhancing Energy Efficiency in Locally Developed Steam Boilers: A Response Surface Methodology Approach. *Research Journal in Civil, Industrial and Mechanical Engineering, 1*(1), 58–72. https://doi.org/10.61424/rjcime.v1i1.153

Onyenanu, I. U., Nwadiuto, C. J., Okeke, chisom V., & Okafor, A. M. (2024). Development of a Mathematical Model for Palm Fruit Digester Design: Integrating Dimensional Analysis and Process Optimization. *International Journal of Applied and Natural Sciences, 2*(2), 15–26. https://doi.org/10.61424/ijans.v2i2.144

Onyenanu, Ifeanyichukwu & Okeke, O & Nwobu, C & Akubuenyi, J & Mgbemeje, A & Okeke, I. (2023). Development of an Enhanced Biomass Gasifier Charcoal Stove. *International Journal of Innovative Science and Research Technology, 8.* 686-694. https://doi.org/10.1126/science.1106881

Organization, W. H., Programme, U. U. N. E., & Health, W. O. for A. (2022). *One health joint plan of action (2022–2026): Working together for the health of humans, animals, plants, and the environment.* World Health Organization.

Owusu, P. A., & Asumadu-Sarkodie, S. (2016). A review of renewable energy sources, sustainability issues, and climate change mitigation. *Cogent Engineering, 3*(1), 1167990. https://doi.org/10.1080/23311916.2016.1167990

Pawaree, N., Phokha, S., & Phukapak, C. (2024). Multi-response optimization of charcoal briquettes process for green economy using a novel TOPSIS linear programming and genetic algorithms based on response surface methodology. *Results in Engineering, 22*, 102226. https://doi.org/10.1016/j.rineng.2024.102226

Saeed, A. A. H., Yub Harun, N., Bilad, M. R., Afzal, M. T., Parvez, A. M., Roslan, F. A. S., Abdul Rahim, S., Vinayagam, V. D., & Afolabi, H. K. (2021). Moisture content impact on the properties of briquette produced from rice husk waste. *Sustainability, 13*(6), 3069.

Sinha, S. N., & Nag, P. K. (2011). Air pollution from solid fuels. *Encyclopedia of Environmental Health, 1*, 46–52.

Somsuk, N., Srithongkul, K., Wessapan, T., & Teekasap, S. (2008). Design and Fabricate a Low-Cost Charcoal Briquette Machine for Small and Micro Community Enterprises. *Proceedings of the 1st International Conference of the Council of Deans of Architecture School Thailand (CDAST 2008), Phitsanulok, Thailand* (pp. 23–25).

Sunardi, S., Djuanda, D., & Mandra, M. A. S. (2019). Characteristics of charcoal briquettes from agricultural waste with compaction pressure and particle size variation as an alternative fuel. *International Energy Journal, 19*(3), 139–148.

Thabuot, M., Pagketanang, T., Panyacharoen, K., Mongkut, P., & Wongwicha, P. (2015). Effect of applied pressure and binder proportion on the fuel properties of holey bio-briquettes. *Energy Procedia, 79*, 890–895.