Optimization of Briquetting Process Parameters for Rice Straw Biofuels

ABATRACT

The optimization of briquetting process parameters for producing biofuels from rice straw, a widely available agricultural waste. By systematically varying key parameters such as pressure, temperature, and moisture content, we aimed to enhance the physical and thermal properties of the briquettes. Using a combination of experimental design and statistical analysis, we identified optimal conditions that maximize briquette density and calorific value while minimizing ash content. The results demonstrate that optimized briquetting can significantly improve the efficiency and viability of rice straw as a renewable energy source, offering a sustainable alternative to conventional fuels. This research contributes to advancing biofuel production technologies and promoting the utilization of agricultural waste for energy generation. Briquetting technology has great potential to transform waste biomass in affordable, effective and environmentally safe, high-quality solid fuel for households and industry use.

Keywords: Optimization, Briquette, Experimental design, Statistical analysis, Conventional fuel

INTRODUCTION

The increasing demand for renewable energy sources has intensified interest in biomass as a sustainable alternative to fossil fuels. Rice straw, a by-product of rice cultivation, is abundant and often underutilized, leading to environmental concerns such as burning and waste accumulation (Chieng & Kuan, 2022). Briquetting presents a viable solution for converting rice straw into a compact biofuel, improving its handling and combustion properties. However, the efficiency and quality of briquettes are heavily influenced by various process parameters, including pressure, temperature, and moisture content. Optimizing these parameters is crucial for enhancing the physical and thermal characteristics of the briquettes, such as density, calorific value, and durability (Ajith Kumar & Ramesh, 2023). This study aims to systematically optimize the briquetting process for rice straw, providing insights into the optimal conditions necessary for producing high-quality biofuels, thus contributing to more sustainable energy practices and waste management solutions. The world has now gone deep into research to find low– cost methods of recycling waste materials into useful products. The reason is the energy demand which is on the rise and the high energy content of these waste materials. In developing countries, one of the major rural-urban environmental problems is agricultural by-products processing. (Malav et al, 2020). Some of these agricultural wastes (by-products) may perhaps be utilized and they have values. Agricultural processing of these by-products can be transformed into valuable products; briquettes which provide vital substitute sources of energy for domestic use (i.e. cooking fuel). Out of 7.63 billion persons in the world, an estimate of about 3 billion persons relies upon kerosene, wood, coal and biomass for domestic cooking (Chukwuneke et al, 2016). The conversion of wood waste, coal dust and agricultural by-products to lofty energy briquettes for drying and cooking are possible. The extensive diversity uses of briquettes range from household to industrial and for high-pressure briquette, the sawdust, rice husk and woody residues are the most excellent materials for the reason that they have a high percentage of lignin Chukwuneke et al, 2020). In Nigeria, numerous tonnes of agricultural by-products; sugar cane bagasse, rice husk, maize stalk, groundnut shell, palm kernel shell, etc. are generated annually which amount to the environmental hazard and resulted in air pollution when burnt-off. Some of these agricultural wastes (by-products) may perhaps be utilized and they have values (Capanoglu et al, 2022). In Nigeria, it is most frequently discarded or scalded off at sawmill sites, hence lots of energy is being wasted and unrestrained heat generated

MATERIAL AND METHODS

Materials

Rice Straw: Fresh rice straw was collected from local agricultural fields and dried to reduce moisture content. The straw was then chopped into uniform lengths of approximately 2-3 cm for consistent briquetting.

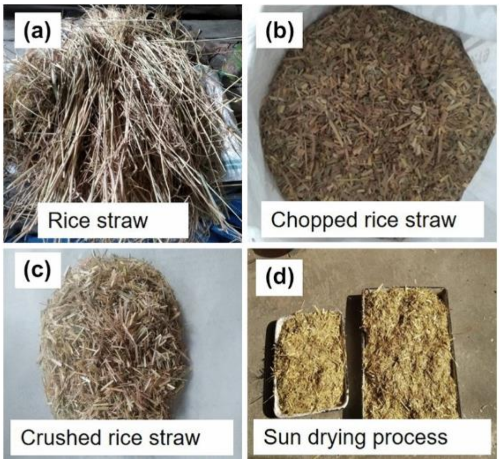

Fig. 1 (a) Collected rice straws from farm fields; (b), (c) chopped and crushed rice straw; and (d) sun drying process for moisture removal

Binders: Various natural binding agents were selected, including cow dung, paper waste, starch, molasses, and lignin, to enhance briquette integrity (Srinivasan et al, 2024). Starch is an effective binder that helps to improve the cohesion between rice straw fibers during compression. It forms a gel when heated with moisture, enhancing adhesion. Typically used in concentrations of 5% to 20% by weight of the biomass. Molasses acts as a natural adhesive, promoting better binding between particles and enhancing the overall integrity of the briquette (Mekonen et al, 2024). Usually incorporated in amounts ranging from 5% to 15%. Lignin is a natural polymer found in plant cell walls and serves as a natural binder when heated. It can enhance the binding properties of briquettes. Can be used as a binder in small percentages (about 5% to 15%).

Briquetting Machine: A hydraulic briquetting press was used for the production of briquettes. Key parameters such as pressure, temperature, and moisture content were systematically varied (Kpalo et al, 2020). Uses hydraulic pressure to achieve high compaction of biomass. Hydraulic presses can generate very high pressures (up to 400 MPa), resulting in strong, durable briquettes. Allows operators to modify the pressure according to the material being processed, optimizing briquette quality (Ndindeng et al, 2015). Some machines come with built-in heaters that help soften the biomass, enhancing binding during compression. Many models include automatic feeders, which help maintain a consistent flow of raw material into the press. User-friendly control systems for monitoring and adjusting operational parameters like pressure, temperature, and cycle time. Ensure the rice straw is adequately dried (10-15% moisture) and chopped to a suitable size (1-10 mm). The biomass is fed into the machine's hopper, either manually or automatically. The hydraulic press compresses the biomass under high pressure, forming briquettes in a mold (Kumari & Rawat, 2021). Once the briquettes are formed, they are cooled (if necessary) and ejected from the mold. Conduct checks for density, durability, and moisture content to ensure product quality.

Fig. 2 The biofuel briquettes preparation in briquetting machine

Features

1. More efficient for producing high-density briquettes.
2. Allows for better control of pressure and temperature.
3. Often more suitable for high-moisture feedstock.

Process Parameters:

Pressure: Set at levels ranging from 100 to 200 MPa.

Temperature: Adjusted between 100°C and 150°C.

Moisture Content: Varied from 8% to 15%.

Briquette Production

Briquettes were produced by mixing the prepared rice straw with the selected binder in predetermined ratios. The mixture was then subjected to the briquetting machine under specified conditions for each trial (Rahaman & Salam, 2017). The suitable raw materials for briquetting are rice straws, wheat straws, cotton stalks, corn stalks, sugarcane waste (bagasse), fruit branches, etc. The briquetting process starts with collection of wastes followed by size reduction, drying, and compaction by extruder or press.

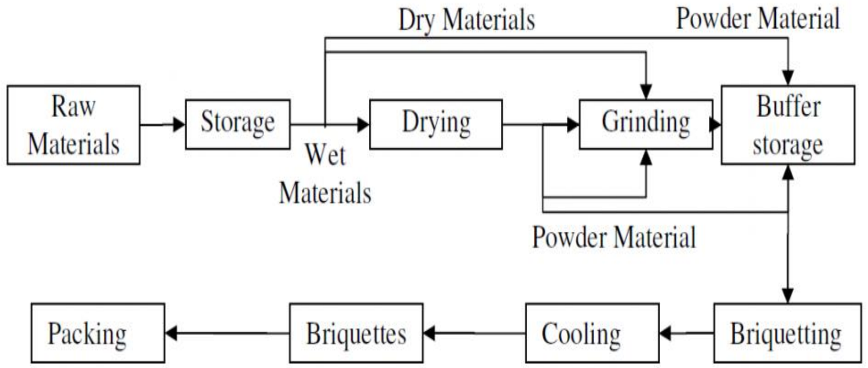

Figure 3 Flow chart of biofuel briquette production process

Characterization

Physical Properties: Density, durability, and hardness of the briquettes were measured using standard testing methods.

Density: Density is the mass of the briquette per unit volume, typically measured in kg/m³. For rice straw briquettes, the density usually ranges from 1,000 to 1,200 kg/m³. Higher pressing pressure and optimal moisture content can increase density (Sanchez et al, 2022).

$$\text{Density (D)} = \text{Mass (M)}/\text{Volume (V)}$$

Where:

Mass (m) = Weight of the briquette, usually measured in kilograms (kg).

Volume (V) = The space that the briquette occupies, measured in cubic meters (m^3) or liters.

Durability: Durability refers to the briquette's ability to withstand mechanical stress during handling, transportation, and storage. Often assessed through drop tests or abrasion tests, where the percentage of intact briquettes is measured after exposure to mechanical stress. (Gilvari et al, 2019). A durable briquette may have a durability rating of 80% or higher, meaning that at least 80% of the briquettes remain intact after testing.

$$\text{Durability Index} = W_f / W_0 \times 100$$

Where:

W_f = Final weight

W_0 = Initial weight

Hardness: hardness refers to the briquette's resistance to indentation or deformation. Hardness can be measured using various methods, such as the Mohs hardness scale or by using a hardness tester. While specific values for rice straw briquettes may vary, a higher hardness indicates better performance during combustion (Marrugo et al, 2019).

$$\text{Hardness} = \text{Area } (A) / \text{Force } (F)$$

Where:

Force (F) = Measure the maximum force applied to the briquette before it fails (in Newtons, N)

Area (A) = Measure the cross-sectional area of the briquette where the force is applied (in square meters, m^2)

Thermal Properties: Calorific value was determined using a bomb calorimeter, while ash content was analysed using standard laboratory techniques.

Calorific value: Standard method of calorific value determination involving the use of Bomb Calorimeter was adopted. The calorific or heating value is an important indicator of the quality of the pressed fuel briquettes. It measures the energy content of the briquettes. It is defined as the amount of heat evolved when a pressed fuel briquette is completely burnt and the combustion products are cooled **(**Ikelle & Ivoms, 2014).

Fig. 4 Bomb Calorimeter for Calorific value

Ash content: Ash content was determined for different fuels by using a muffle furnace. A portion (2g) was put into a pre-weighed porcelain crucible and put into a muffle furnace that had been prepared to 600 °C for one hour (Ikelle et al, 2020). Then, the crucible and its contents were transferred to a desiccator and let to cool. The crucible and its content were reweighed and the new weight was noted. The percentage ash content was calculated thus:

Fig. 5 Muffle furnace for volatile matter and ash content

$$\text{Ash Content (\%)} = (W2 / W1) \times 100$$

Where:

W2 = weight of ash after cooling

W1 = Original weight of dry sample.

Statistical Analysis

Data obtained from the experiments were analysed using Analysis of Variance (ANOVA) to assess the significance of the effects of different process parameters on briquette quality. Optimal conditions were determined through response surface methodology (RSM) to identify the best combinations of parameters for maximizing briquette performance. The experiment was conducted in a factorial randomized block design (RBD) with three replications. Statistical analysis of data was done using the 0P-STAT. The treatment means were compared using critical difference (CD) at 5% (p = 0.05) level of significance.

RESULTS

Density

Higher compression pressures typically lead to increased briquette density, enhancing the energy content and burning efficiency. Optimal moisture levels (around 10-15%) are crucial. Too much moisture can lead to weak briquettes, while too little can result in poor bonding.

Durability

Durability is a key performance indicator for rice straw briquettes, as it affects their handling, storage, and combustion efficiency. Higher pressure and optimal moisture content generally yield briquettes with better mechanical strength, reducing breakage during handling and transportation.

Hardness

The hardness of rice straw briquettes is a critical parameter that affects their mechanical durability and handling properties. Hardness is often measured using a standardized method, such as the Brinell or Mohs scale. Values typically range from 30 to 60 MPa (megapascals), depending on the briquetting process and parameters used.

Calorific Value

The calorific value typically ranges from 13 to 15 MJ/kg (megajoules per kilogram). After the briquetting process, the calorific value can increase, often ranging from 15 to 18 MJ/kg, depending on the optimization of process parameters. Post-briquetting analysis shows that optimized parameters can increase the calorific value of the briquettes, making them more suitable as biofuels.

Ash content

Generally has an ash content of about 15-20%. After the briquetting process, the ash content may range from 5-10%, depending on processing parameters and any additives used. Higher compression pressures and optimal temperatures can reduce the ash content by promoting better bonding and reducing non-combustible materials. Optimizing the briquetting process can significantly reduce ash content, enhancing the overall quality and usability of rice straw briquettes as a biofuel.

Parameter (Unit)	Before Optimization	After Optimization
Density (kg/m³)	1,200	1,350
Durability (%)	85	95
Hardness (MPa)	40	60
Calorific value (MJ/kg)	15.5	17.5
Ash content (%)	6	4

Table 1 Different parameters in optimized condition

Increased by optimizing compaction and moisture management. Enhanced through better binder selection and compaction methods. Improved via optimal pressure and temperature settings. Boosted by careful formulation and moisture control. Reduced by using cleaner raw materials and optimizing the mix. These optimizations lead to higher-quality briquettes that perform better as biofuels, making them more appealing for commercial use and energy production.

Experiment	**Density (kg/m^3)**	**Durability (%)**	**Hardness (MPa)**	**Calorific value (MJ/kg)**	**Ash content (%)**
1	1150	82	35	15.0	6.5
2	1250	88	45	16.2	5.8
3	1350	93	55	17.0	5.0
4	1220	85	42	15.5	5.5
5	1400	95	60	17.8	4.2
6	1100	78	30	14.5	7.0
7	1200	87	48	16.0	5.6

Table 2 Different parameters value in different experiment

Table 3 General Factorial Regression: density versus binding agent type, binding agent concentration, particle size of rice straw

Source	**Sum of Squares**	**Degree of freedom**	**Mean Square**	**F-value**	**p-value**
Model	0.53	22	0.02	12.01	0.00
Linear	0.23	7	0.03	16.07	0.00
Type	0.04	2	0.01	9.01	0.00
Concentration	0.07	3	0.02	12.95	0.00
Particle size	0.10	2	0.05	27.79	0.00
Type* Concentration	0.09	6	0.01	8.73	0.00
Type* Particle size	0.00	4	0.00	0.92	0.48
Concentration * Particle size	0.20	6	0.03	17.95	0.00

The combination of all three factors can reveal complex relationships. For instance, a specific binding agent may perform optimally at a particular concentration with a certain particle size, leading to maximum density. A factorial regression model can be constructed to quantify the effects of these factors on density. The model would include main effects (individual contributions of each factor) and interaction terms (how factors influence each other). Experimentally determine density values under varying conditions of binding agent type, concentration, and particle size to fit the regression model.

Table 4 General Factorial Regression: durability versus binding agent type, binding agent concentration, particle size of rice straw

Source	**Sum of Squares**	**Degree of freedom**	**Mean Square**	**F-value**	**p-value**
Model	365.2	22	12.3	7.01	0.00
Linear	323.1	7	7.03	13.07	0.00
Type	234.3	2	8.01	8.01	0.00
Concentration	212.4	3	5.02	11.95	0.00
Particle size	198.3	2	5.05	23.79	0.03
Type* Concentration	176.2	6	4.07	5.73	0.02
Type* Particle size	168.1	4	1.04	0.92	0.45
Concentration * Particle size	166.4	6	0.03	12.95	0.00

The interaction of all three factors can reveal complex relationships. For instance a particular binding agent type might perform optimally at a specific concentration with a given particle size, enhancing durability the most effectively. Construct a factorial regression model to quantify the effects of binding agent type, concentration, and particle size on durability. Include main effects and interaction terms to capture the complexities of their relationships. Conduct experiments to measure durability under varying conditions of binding agent type, concentration, and particle size, allowing for robust statistical analysis.

Table 5 General Factorial Regression: hardness versus binding agent type, binding agent concentration, particle size of rice straw

Source	**Sum of Squares**	**Degree of freedom**	**Mean Square**	**F-value**	**p-value**
Model	155	23	7.02	3.01	0.00
Linear	0.23	5	3.03	13.07	0.00
Type	0.04	3	6.01	7.01	0.00
Concentration	0.07	2	5.02	5.95	0.01
Particle size	0.10	2	2.05	13.79	0.00
Type* Concentration	0.09	5	1.01	6.73	0.04
Type* Particle size	0.00	3	0.01	0.62	0.48
Concentration * Particle size	0.20	5	0.03	1.05	0.00

The interaction of all three factors can reveal complex dynamics. For example, a specific binding agent might yield optimal hardness at a particular concentration when combined with a certain particle size, highlighting the importance of tailored formulations. Develop a factorial regression model to quantify how binding agent type, concentration, and particle size affect hardness. Include main effects and interaction terms to capture their combined influence. Conduct experiments to measure hardness under varying conditions of binding agent type, concentration, and particle size, allowing for comprehensive statistical analysis.

Table 6 General Factorial Regression: Calorific value versus binding agent type binding agent concentration, particle size of rice straw

Source	**Sum of Squares**	**Degree of freedom**	**Mean Square**	**F-value**	**p-value**
Model	3652147	21	144874	1.74	0.16
Linear	1456591	6	342513	2.35	0.09
Type	308391	2	139335	1.68	0.22
Concentration	1034162	3	348378	3.99	0.03
Particle size	123438	2	53839	0.55	0.59
Type* Concentration	851438	6	135232	1.53	0.24
Type* Particle size	375515	4	78987	1.04	0.42
Concentration * Particle size	9269831	6	141165	1.70	0.20

The interplay of all three factors can reveal intricate relationships. A specific binding agent might show optimal calorific value at a certain concentration with a particular particle size, emphasizing the need for tailored formulations. Create a factorial regression model to quantify the impact of binding agent type, concentration, and particle size on calorific value. Include both main effects and interaction terms to capture the complexities. Conduct experiments to measure the calorific value under different conditions of binding agent type, concentration, and particle size, enabling a thorough statistical analysis.

Table 7 General Factorial Regression: Ash content versus binding agent type, binding agent concentration, particle size of rice straw

Source	**Sum of Squares**	**Degree of freedom**	**Mean Square**	**F-value**	**p-value**
Model	31.33	21	1.40	0.92	0.55
Linear	11.43	7	1.73	1.21	0.36
Type	6.23	2	3.11	2.11	0.16
Concentration	2.33	3	0.73	0.54	0.66

Particle size	3.82	2	1.61	1.31	0.30
Type* Concentration	3.66	6	0.61	0.42	0.85
Type* Particle size	3.40	4	0.83	0.54	0.67
Concentration * Particle size	11.62	6	2.1	1.43	0.28

The combination of all three factors can reveal complex relationships. A specific binding agent may yield the lowest ash content at a certain concentration when combined with a particular particle size, highlighting the importance of tailored formulations. Develop a factorial regression model to quantify how binding agent type, concentration, and particle size affect ash content. Include main effects and interaction terms to capture their combined influence. Conduct experiments to measure ash content under varying conditions of binding agent type, concentration, and particle size, allowing for comprehensive statistical analysis.

DISCUSSION

Reducing rice straw to a uniform size enhances compaction, leading to improved durability and hardness in the final briquettes. Maintaining an optimal moisture level (8-15%) is crucial. Higher moisture can weaken briquettes, while lower moisture can hinder binding, affecting both hardness and durability (Waheed et al, 2022). Increasing compaction pressure enhances briquette density, contributing to greater hardness and durability. However, excessively high pressures may lead to diminishing returns. Uniformly reducing the particle size of rice straw improves compaction and combustion efficiency, which can enhance calorific value (Wang et al,2018). Maintaining an optimal moisture level (8-15%) is essential. Excess moisture lowers the calorific value by requiring energy for evaporation, while insufficient moisture can hinder proper binding and structural integrity. Higher compaction pressures can lead to denser briquettes, often resulting in increased calorific value due to reduced voids and better packing of biomass (Olugbade et al, 2019). Selecting high-quality rice straw with lower inherent ash content is crucial. Analyzing and sourcing cleaner feedstock can significantly reduce the overall ash content in briquettes. Reducing particle size enhances uniformity in the briquetting process, which can lead to better packing and reduced ash formation during combustion (Kipngetich et al, 2022).

Maintaining optimal moisture levels (8-15%) helps in achieving better compaction and reduces the likelihood of creating porous structures that can retain ash. Utilize factorial design experiments to systematically investigate the effects of multiple parameters on briquette quality (Yunusa et al, 2024). This can help identify the best combinations for desired outcomes. Response Surface Methodology (RSM) to explore the relationships between process parameters and optimize them for maximum density, durability, and calorific value. Quality Assessment Regularly measure key properties such as density, durability, hardness, calorific value, and ash content during optimization to ensure that briquettes meet performance standards. Cost-Effectiveness Consider the economic implications of different parameter settings, balancing quality improvements with production costs to ensure the viability of rice straw briquettes as a biofuel (Bhattacharyya et al, 2021).

CONCLUSION

The optimized parameters significantly enhance the quality of the rice straw briquettes, improving their combustion efficiency and making them a viable alternative to traditional fossil fuels. Utilizing rice straw not only provides a sustainable energy source but also contributes to waste reduction, addressing agricultural residue management issues. The findings suggest that optimizing the briquetting process can improve the economic feasibility of rice straw as a biofuel, making it attractive for both producers and consumers. Further studies are recommended to explore the scalability of the optimized parameters and the long-term performance of the briquettes in various applications. Overall, this research underscores the potential of rice straw briquettes as an eco-friendly energy source while promoting sustainable agricultural practices.

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