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. Through experimental design and statistical analysis, we identified optimal conditions to maximize briquette density and calorific value while minimizing ash content. The findings show that optimized briquetting greatly enhances the efficiency and potential of rice straw as a renewable energy source, providing a sustainable alternative to traditional 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. This study focuses on optimizing the briquetting process for rice straw to enhance its quality as a biofuel. Key parameters, including compaction pressure, moisture content, binding agent type, and particle size, were systematically varied to improve density, durability, hardness, calorific value, and reduce ash content. Results indicate significant improvements in briquette performance, with calorific values increasing to 17.5 MJ/kg and ash content reducing to 4%. Optimized briquettes offer enhanced mechanical strength and combustion efficiency, positioning rice straw briquettes as a viable, eco-friendly alternative to traditional fossil fuels, contributing to sustainable energy and agricultural residue management.

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*). The problem of agricultural waste in Nigeria is both widespread and serious, with vast quantities of by-products generated every year. These include materials like sugarcane bagasse, rice husk, maize stalks, groundnut shells, and palm kernel shells. While they could potentially have valuable uses, they are often treated as waste and are either discarded or burned off. The latter practice, common at sawmill sites, not only wastes a significant amount of energy but also contributes to environmental hazards. The resulting air pollution is harmful, as the uncontrolled burning releases heat and emissions into the atmosphere.

Nigeria's agricultural sector produces large quantities of waste annually, a by-product of its diverse farming activities. This waste, including sugarcane bagasse, rice husk, maize stalk, groundnut shell, and palm kernel shell, often poses a threat to the environment when improperly disposed of. Instead of being repurposed or harnessed for energy or other beneficial uses, these by-products are frequently burned. The open-air burning of these materials leads to unregulated heat production and the release of pollutants into the environment, contributing to air quality degradation and climate concerns.

One of the major challenges faced by the country’s agricultural and industrial sectors is the inefficient handling of these by-products. While agricultural residues such as rice husks, groundnut shells, and maize stalks hold potential for generating energy or serving as raw materials in various industries, they are instead seen as waste. This leads to their large-scale incineration, a process that not only results in the squandering of energy resources but also exacerbates environmental pollution. The generation of heat and harmful emissions from burning these materials affects air quality and contributes to the broader issue of environmental sustainability.

Despite the growing recognition of the potential value of these agricultural by-products, Nigeria’s waste management practices continue to be suboptimal. The abundance of materials like palm kernel shells and maize stalks could be better utilized in industries such as bioenergy production, construction, or as organic fertilizers. However, the current tendency to dispose of these resources through burning highlights a missed opportunity for energy conservation and environmental protection. The environmental toll of such practices is substantial, as the uncontrolled release of carbon and other pollutants into the atmosphere accelerates the degradation of air quality, adding to the already significant challenges posed by climate change and industrial emissions.

In addition to the environmental concerns, the wasteful handling of agricultural by-products represents a lost opportunity for economic gain. Agricultural waste can be repurposed into bioenergy, biofuels, or used as raw materials for industries such as paper production, animal feed, and bio-based packaging materials. The lack of infrastructure and investment in converting these by-products into valuable resources continues to hold back the country's potential for sustainable industrial growth. Instead of harnessing the energy and economic value of materials like rice husk and sugarcane bagasse, the country is left dealing with the detrimental effects of air pollution and the loss of renewable energy sources. The issue of agricultural waste burning is a significant contributor to the environmental hazards Nigeria faces today. The open burning of materials like maize stalk and palm kernel shell at sawmills and agricultural sites creates a cloud of harmful emissions that degrades the quality of the air. This practice is not only dangerous for the environment but also poses health risks to nearby populations due to the release of particulate matter and other harmful substances into the atmosphere. As the world grapples with climate change and the need for sustainable solutions, Nigeria's inefficient waste management practices serve as a reminder of the critical need to find better ways to handle agricultural by-products. By recognizing the potential value of agricultural by-products and investing in technologies that can convert waste into energy or other useful products, Nigeria could take a step toward addressing both its energy needs and environmental challenges. Bioenergy production, for example, could provide a renewable energy source that helps reduce the nation's reliance on fossil fuels while simultaneously reducing the environmental impact of agricultural waste. Alternatively, these by-products could be processed into raw materials for industries such as construction, packaging, or animal feed, adding value to what is currently considered waste.

Ultimately, the problem of agricultural waste management in Nigeria is one that requires urgent attention. The current practices of burning and discarding by-products are not only wasteful but also harmful to the environment. By adopting more sustainable waste management practices and recognizing the value of agricultural by-products, the country can reduce air pollution, conserve energy, and create economic opportunities. The challenge lies in shifting from a wasteful mindset to one that sees agricultural by-products as valuable resources capable of contributing to sustainable development and environmental protection.

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.

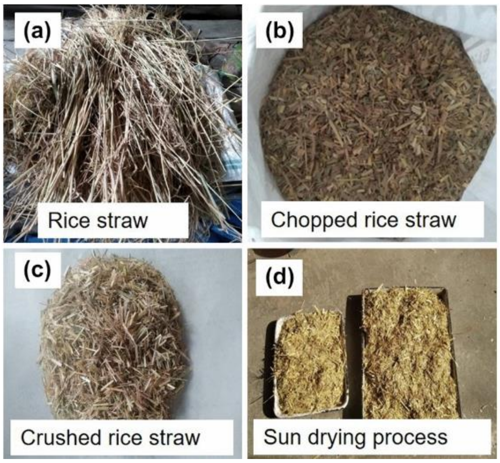

Fig. 1 (a) Collected rice straws from farm fields; (b), (c) chopped and crushed rice straw; and (d) sun drying process for moisture removal

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.

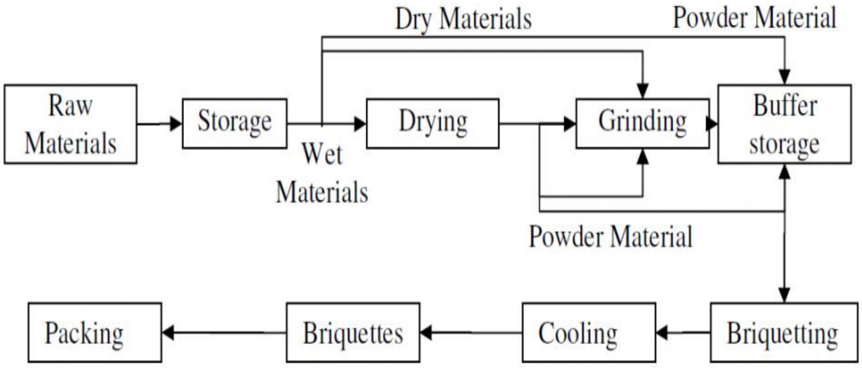

Fig. 3 Flow chart of biofuel briquette production process

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 (m³) 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 AND DISCUSSION

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. Durability index: **80-95%**. A high durability index means the briquettes can withstand mechanical stress during handling and transportation with minimal degradation.

Hardness

The hardness of rice straw briquettes plays a vital role in determining their mechanical durability, handling, and overall performance in various applications, particularly in energy production and materials handling systems. Hardness is an essential mechanical property that directly influences how well briquettes withstand compressive forces, resist breakage, and maintain structural integrity during transportation, storage, and utilization. As such, understanding and optimizing the hardness of rice straw briquettes is crucial for improving their quality, performance, and commercial viability in bioenergy and other industries. In scientific terms, hardness can be defined as the resistance of a material to deformation or indentation under applied stress. For rice straw briquettes, hardness is typically quantified through standardized testing methods, such as the Brinell or Mohs hardness scales, both of which measure the ability of the material to resist localized plastic deformation. The Brinell hardness test, for instance, involves applying a known force to a briquette using a hard indenter (usually a steel or tungsten carbide ball) and then measuring the diameter of the resulting indentation. The hardness value is then calculated based on the applied force and the indentation's surface area. Similarly, the Mohs scale ranks the hardness of materials on a relative scale from 1 to 10, where softer materials like talc are at the lower end and harder substances like diamond are at the upper end. For rice straw briquettes, hardness values typically range between 30 and 60 MPa (megapascals), though these values can vary depending on several factors related to the briquetting process. These factors include the moisture content of the straw, the pressure applied during briquetting, the temperature conditions, and any binding agents used. Higher pressure during the briquetting process generally results in denser, harder briquettes, as the applied force compacts the rice straw particles more tightly, thereby increasing the mechanical interlocking between fibers. This compaction also reduces the void spaces within the briquette, leading to improved structural integrity and higher hardness values. Conversely, lower pressures or suboptimal processing conditions can result in briquettes with lower hardness, reduced durability, and increased susceptibility to breakage during handling.

Moisture content is another critical factor influencing the hardness of rice straw briquettes. Briquettes with excessive moisture may have lower hardness values, as the presence of water can weaken the inter-particle bonds and make the briquettes more prone to deformation under stress. On the other hand, if the moisture content is too low, the rice straw may not bind properly during the briquetting process, leading to brittleness and reduced durability. Optimizing the moisture content is therefore essential for achieving the desired hardness and mechanical strength of the briquettes.

The choice of binding agents, if used, can also significantly affect the hardness of rice straw briquettes. Natural or synthetic binders can enhance the cohesion between rice straw particles, leading to increased hardness and improved durability. Common binders used in briquetting processes include starch, molasses, and lignin, which act to reinforce the structural integrity of the briquettes by forming strong inter-particle bonds. In addition to the briquetting parameters, the intrinsic properties of the rice straw itself, such as its fiber composition and lignin content, can influence the hardness of the resulting briquettes. Rice straw contains cellulose, hemicellulose, and lignin, which provide the mechanical framework for the briquette. Lignin, in particular, plays a key role in binding the fibers together during the briquetting process, contributing to the overall hardness and strength of the briquette. The thermal conditions during briquetting can also influence the softening and plasticization of lignin, which enhances the bonding between particles and leads to harder, more durable briquettes. It’s mean, the hardness of rice straw briquettes is a critical factor that affects their mechanical durability, handling properties, and suitability for various applications. Hardness is influenced by a range of variables, including the pressure applied during the briquetting process, moisture content, the use of binding agents, and the inherent properties of the rice straw. By optimizing these parameters, the mechanical strength and performance of rice straw briquettes can be significantly enhanced, making them more suitable for use in bioenergy production and other industries that require durable, high-quality briquettes. Values typically range from 30 to 60 MPa (megapascals), depending on the briquetting process and parameters used. Hardness: **5-8 MPa** (depending on the compaction pressure and binder type used). Hardness measures the briquettes' resistance to deformation and breakage, indicating good structural integrity.

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. Calorific value: **16-17.5 MJ/kg**.

This is the amount of energy the briquettes release when burned, indicating their potential as a heat source.

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.

Table 1 Different parameters in optimized condition

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

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.

Table 2 Different parameters value in different experiment

Experiment	Density (kg/m³)	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 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. Ash content: **3-5%.** Lower ash content improves combustion efficiency and reduces residue after burning.

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.

Volatile Matter: Volatile matter: 60-70% and volatile matter represents the portion of the briquette that vaporizes upon heating, playing a key role in combustion. Volatile matter in briquettes refers to the components that vaporize when the briquette is heated, such as gases, tar, and organic compounds. In rice straw briquettes, volatile matter typically constitutes 60-70% of the total mass. When exposed to heat, these volatile substances are released, igniting quickly and contributing to the combustion process. The high volatile matter content is crucial because it determines the ease of ignition and flame propagation, making briquettes burn more readily. However, balancing volatile matter with other components like fixed carbon and ash content is important to ensure efficient, sustained combustion and energy output.

Fixed Carbon: Fixed carbon: 15-20%. This is the solid carbon remaining after the volatile matter is released during combustion, contributing to the burning efficiency. Fixed carbon in briquettes refers to the solid residue that remains after the volatile matter has been released during combustion. In rice straw briquettes, fixed carbon typically ranges between 15-20%. This component is crucial as it represents the fraction of the briquette that provides sustained, long-lasting heat during the burning process. Unlike volatile matter, which ignites quickly, fixed carbon burns more slowly, contributing to the briquette’s overall burning efficiency. Higher fixed carbon content ensures that after the initial ignition, the briquette continues to generate heat steadily, making it an efficient source of energy for prolonged use.

Moisture Content: Moisture content: 8-12%. Optimal moisture levels ensure better compaction and combustion. Too much moisture lowers the calorific value and weakens the briquettes. Moisture content in rice straw briquettes is a critical parameter that typically ranges from 8-12%. Maintaining optimal moisture levels is essential for achieving effective compaction during the briquetting process, as it enhances the bonding between fibers and ensures structural integrity. Additionally, appropriate moisture content facilitates efficient combustion by allowing the briquettes to ignite and burn uniformly. However, excessive moisture can be detrimental, as it not only lowers the calorific value—thereby reducing the energy output—but also weakens the briquettes, making them more prone to disintegration and reducing their durability during handling and storage. Consequently, controlling moisture content is vital for producing high-quality briquettes that deliver optimal performance as a biofuel.

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 critical, as excess moisture reduces calorific value by consuming energy for evaporation, while too little moisture weakens binding and structural integrity. Increased compaction pressure produces denser briquettes, enhancing calorific value by reducing void spaces and improving biomass packing (Olugbade *et al*, 2019). Using high-quality rice straw with lower inherent ash content is key, as cleaner feedstock can greatly reduce ash in the final briquettes. Additionally, reducing particle size improves briquette uniformity, leading to better packing and less ash production 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 is critical to ensuring that rice straw briquettes meet desired performance standards. Regular monitoring of essential properties such as density, durability, hardness, calorific value, and ash content throughout the optimization process is necessary. This approach helps maintain consistency in the production of high-quality briquettes that align with industry requirements. Measuring these parameters allows for early identification of any deviations and ensures that adjustments can be made to optimize the process effectively. In parallel, cost-effectiveness must be a key consideration during the optimization of briquetting parameters. While it is essential to improve the quality of the briquettes, it is equally important to evaluate the economic feasibility of the chosen parameters. Achieving the right balance between performance enhancements and production costs is vital to ensure the commercial viability of rice straw briquettes as a biofuel. Excessive improvements in quality should not result in unsustainable production expenses that undermine the economic benefits of using rice straw as a renewable energy source. By carefully assessing both quality metrics and cost factors, producers can optimize the briquetting process to yield briquettes that not only meet technical standards but are also financially viable for large-scale production. This balance will support the wider adoption of rice straw briquettes as a cost-effective, eco-friendly biofuel alternative to conventional energy sources. (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. The optimization of briquetting process parameters for rice straw significantly enhances its potential as a biofuel by improving both physical and thermal properties of the briquettes. Key factors such as compaction pressure, moisture content, and binder type were found to directly influence briquette density, durability, hardness, and calorific value. The systematic variation and control of these parameters, as well as statistical analysis using Response Surface Methodology (RSM), led to the production of briquettes with calorific values reaching 17.5 MJ/kg and reduced ash content to as low as 4%. These results demonstrate that proper optimization not only increases the mechanical strength and combustion efficiency of the briquettes but also makes rice straw a viable and sustainable alternative to fossil fuels. Moreover, the study highlights the importance of balancing process improvements with economic feasibility. While enhancing briquette quality is crucial, ensuring that production remains cost-effective is key for commercial viability.

The findings emphasize that optimized rice straw briquettes can provide a sustainable, eco-friendly solution for energy generation, reducing dependence on traditional fuels while mitigating environmental concerns related to agricultural waste disposal. By adopting optimized briquetting processes, rice straw and other agricultural residues can be effectively transformed into high-quality biofuels, contributing to both energy sustainability and better waste management practices. 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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1.

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