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Exploring Biochar Briquettes from Biomass Waste for Sustainable Energy

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Abstract. The increasing demand for renewable energy necessitates sustainable alternatives such as biochar briquettes derived from agricultural waste. This study aims to optimize the production process and evaluate the physical, mechanical, and combustion properties of biochar briquettes made from corn residues, rice husks, and coconut shells. The methodology includes biomass carbonization, binder ratio optimization, and systematic testing of key quality parameters such as moisture content, density, ash content, and calorific value. Results indicate that an optimal biomass-to-binder ratio yields a high calorific value (7,192 kcal/kg) and low ash content (3.57%), enhancing combustion efficiency. Maintaining moisture content below 10% enhances ignition and prolongs burning time. These findings highlight biochar briquettes' role in carbon sequestration, biomass conversion, and sustainable waste management, supporting the circular economy and reducing environmental pollution. Biochar briquettes offer a clean, accessible energy solution, contributing to global energy security and climate change mitigation.

Keywords: Biochar briquettes, biomass conversion, carbon sequestration, calorific value, moisture content, renewable energy

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1. Introduction

The growing global demand for sustainable and renewable energy sources has significantly increased interest in biochar briquettes derived from agricultural waste. Biochar is a charcoal fuel from biomass materials such as wood, twigs, leaves, straw, and other agricultural residues. This renewable energy source offers several advantages, including environmental sustainability, high calorific value, and flexibility in production and application [1][2][3]. However, to maximize its utility, biochar requires further processing into briquettes, which are more efficient and practical for widespread use [3][4][5].

The abundance of waste from the process of life development requires innovative solutions [6]. Waste that is abundant and has great potential is agricultural waste [7]. Agricultural waste such as corn cobs, rice husks, sugarcane bagasse, water hyacinth, and coconut shells represent abundant yet underutilized resources for biochar briquette production. These materials can be transformed into high-energy-density solid fuels through carbonization and briquetting processes [8][9]. Converting agricultural waste into biochar briquettes aligns with the zero-waste concept by reducing environmental pollution and adding economic value to typically discarded materials [10][11]. Moreover, the development of biochar briquettes supports the circular economy by promoting waste valorization and creating opportunities for local communities [8][12].

Biochar briquettes offer several advantages over conventional fuels. They have a higher calorific value—ranging between 5,000–7,000 kcal/kg—compared to raw biomass (~3,000 kcal/kg), produce minimal smoke or odor during combustion, and feature a compact, customizable shape and size [13]. These attributes make them particularly suitable for urban households with limited ventilation and industries seeking cleaner energy alternatives. Furthermore, the simplicity of the production process, which requires minimal technological input, makes biochar briquettes an accessible solution for rural communities [14][15].

The production process involves two main stages: (1) biomass carbonization through pyrolysis—a thermal decomposition process in an oxygen-free environment—and (2) briquette formation using binders such as starch or clay. Pyrolysis converts biomass into charcoal and produces by-products like CO, CH_4, and H_2 gases, which can be utilized for additional energy applications [16][17]. The efficiency of pyrolysis depends on particle size, temperature, moisture content, and raw material composition. For instance, corn cobs and coconut shells are particularly suitable due to their high lignocellulosic content—comprising cellulose (32–45%), hemicellulose (19–36%), and lignin (6–36%)—which enhances carbon yield during pyrolysis [4][18].

Research has shown that biochar briquettes possess higher energy content and enhanced combustion efficiency compared to raw biomass, making them a practical alternative to fossil fuels for both industrial and residential use [19]. In Africa, for example, the use of biochar briquettes has notably lowered household energy expenses and helped mitigate deforestation by serving as an efficient replacement for firewood [20]. Additionally, their production contributes to waste management by transforming organic residues into valuable energy sources, thereby minimizing greenhouse gas emissions from waste decomposition and open burning. These benefits support the United Nations' Sustainable Development Goals (SDGs), particularly in promoting affordable clean energy (SDG 7) and addressing climate change (SDG 13) [21]. The calorific value of biochar briquettes varies based on the composition of raw materials. Previous studies have reported calorific values ranging from 2,912 to 7,192 kcal/g depending on the feedstock used. For example, corn cobs yield 2,912–6,757 kcal/g, rice husks mixed with coal produce approximately 5,100 kcal/g, while coconut shells can reach up to 7,192 kcal/g [22][10]. Despite these promising results, challenges remain in achieving consistent quality standards. Factors such as incomplete carbonization and high moisture content often limit the performance of biochar briquettes [17][10].

This research is critical given the global challenges in meeting renewable energy needs and managing agricultural waste. With a growing population and increasing energy demand, the reliance on fossil fuels has become unsustainable. Biochar briquettes from agricultural waste offer an innovative solution by utilizing abundant and often overlooked resources such as corn cobs, rice husks, and coconut shells. Recent studies show that using biochar briquettes benefits both the environment and the economy. In

Kenya, for instance, local industries use non-carbonized briquettes instead of firewood for tea drying, helping to save millions of trees each year [21]. Biochar production also supports farmers by creating a market for agricultural waste, improving rural incomes [23]. By reducing waste and promoting greener practices, they contribute to a circular economy and global sustainability goals [24]. Carbonization and briquetting processes enhance the calorific value of these wastes and reduce greenhouse gas emissions from waste burning or disposal. This study aims to optimize briquette formulations by varying the biomass-to-binder ratio and evaluating their physical and mechanical characteristics. The findings will highlight the potential of biochar briquettes as an efficient, clean energy source, supporting the transition towards a circular economy and environmental sustainability.

2. Methods

2.1. Research Design

This study was conducted in two stages to evaluate the production and application of biochar briquettes derived from agricultural waste, specifically corn cobs, rice husks, and coconut shells. Corn cobs, a byproduct of maize harvesting, are rich in cellulose and hemicellulose, making them a promising raw material for biochar production due to their moderate calorific value and relatively low ash content. This research uses corn cobs from Zea mays saccharata Sturt (sweet corn) due to the abundance in the surroundings. Rice husks, the outer protective layer of rice grains, are known for their high silica content, which influences the ash composition and thermal stability of the resulting briquettes. It was used as planting media or farming. Coconut shells, characterized by their high lignin and fixed carbon content, contribute to enhanced combustion properties and increased briquette durability. This research uses any kind of old coconut shell that can easily be found in the neighborhoods. The first stage focused on producing biochar briquettes by varying the biomass-to-binder ratio, and then testing their physical and mechanical properties against commercial quality standards [21], [25]. Parameters such as moisture content, density, calorific value, ash content, volatile matter, carbon content, and compressive strength were measured. In the second stage, the briquettes were tested for practical application through a water boiling test to assess their combustion performance, particularly their burning rate [26], [27].

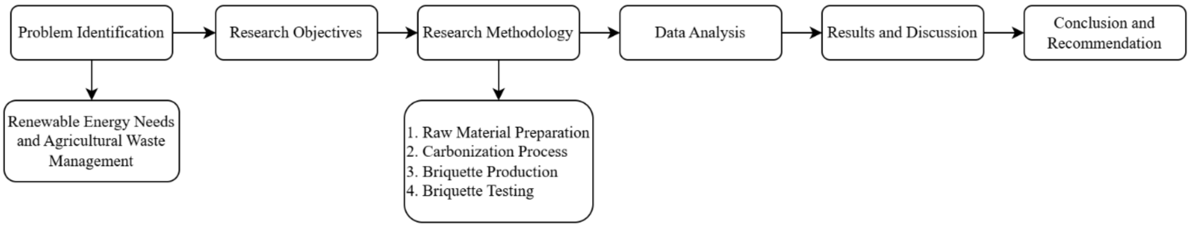

Figure 1. Research Framework

2.2. Production of Biochar Briquettes

The production of biochar briquettes followed these steps:

a. Raw Material Selection and Preparation

1. **Selection Criteria**: Corn residues, rice husks, and coconut shells were chosen for their availability, high lignocellulosic content, and potential for sustainable waste management in tropical agricultural systems [28], [29]. These materials are widely generated as agricultural by-products and align with the study's objective of promoting circular bioeconomy practices [30].
2. **Preparation**: Materials were chopped into smaller pieces (≤5 cm) and sun-dried for 3–7 days to reduce moisture content to below 15%, ensuring efficient carbonization[31], [32].

b. Carbonization Process

1. **Pyrolysis Conditions**: The biomass was carbonized in a furnace under limited oxygen conditions at 500°C for 4 hours [31]. This temperature was selected as it balances biochar yield with enhanced carbon content and reduced volatile matter [32], [33].

2. **Residence Time**: A holding time of 60 minutes was maintained to optimize carbonization efficiency while minimizing energy consumption [31].

c. Grinding and Sieving

The cooled biochar was ground using a mechanical grinder to achieve uniform particle size. Sieving through a 100-mesh screen ensured fine particles suitable for briquette formation [33].

d. Binder Preparation

Tapioca starch, chosen for its low cost and adhesive properties, was prepared in a 1:3 ratio (starch:water) by heating until a clear gel formed.

e. Sample Variations

Five sample variations were prepared to investigate the impact of binder ratios on briquette properties:

1. Sample A: 80:20
2. Sample B: 75:25
3. Sample C: 70:30
4. Sample D: 65:35
5. Sample E: 60:40

f. Briquette Molding

The mixtures were molded into cylindrical shapes (1.5 inches in diameter, 5 cm in height) using a hydraulic press at a pressure of 10 MPa. The briquettes were air-dried for three days to achieve structural stability before testing [33].

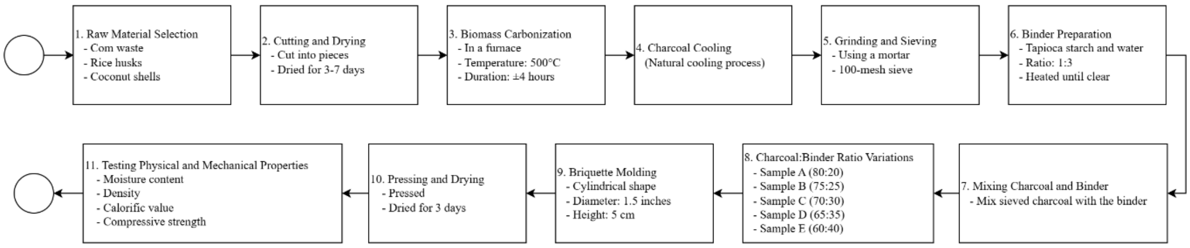

Figure 1. Biochar Briquette Production Process

2.3. Product Testing

The biochar briquettes underwent several tests to evaluate their quality:

a. Physical and Mechanical Properties

1. Moisture Content:

A 5 g sample was dried at 105°C for 4 hours, with weight differences used to calculate moisture content.

2. Density:

Calculated by dividing the mass of each briquette by its volume.

3. Compressive Strength:

Measured using a universal testing machine to assess mechanical stability.

b. Combustion Performance

1. Calorific Value:

Determined using an oxygen bomb calorimeter to measure energy content.

2. Burning Rate:

Assessed through a water boiling test using 2 liters of water in a modified stove setup [33]. Parameters included burning time, mass loss, and flame temperature.

c. Chemical Properties

1. Ash Content:

A 1 g sample was burned at 850°C for 4 hours until only ash remained.

2. Volatile Matter Content:

Heated at 900°C for 7 minutes; the weight loss was used to calculate volatile matter.

3. Carbon Content:

Calculated using the formula:

Carbon Content (%) = 100% - (Moisture Content + Ash Content + Volatile Matter Content).

2.4. Limitations

The methodology acknowledges potential challenges in scaling up production due to variability in feedstock properties and logistical constraints such as transportation costs [30], [34]. Future studies should explore mobile pyrolysis units or decentralized production systems to address these issues effectively. While the study provides valuable insights into biochar briquette production, limitations include variability in feedstock composition and challenges in replicating results across different agricultural regions [32]. Further research is needed to evaluate long-term environmental impacts and economic feasibility.

3. Results and Discussion

The research on producing biochar briquettes from a mixture of corn waste, rice husks, and coconut shells revealed significant insights into the physical and mechanical properties of the resulting briquettes. The methodology employed included carbonization, mixing with binders, pressing, and subsequent testing of various parameters. Below is a detailed discussion of the findings (Table 1).

Table 1. Test Result

No	Charcoal Briquette Composition: Adhesive (%)	Initial Mass (grams)	Final Mass (grams)	Briquette Water Content (%)	Volume (cm3)	Density (g/cm3)	Volatile Matter Content (%)	Ash Content (%)	Bound Carbon (%)	Burning Time (minutes)
1	A (80:20)	15,6	15	4	17,27	0,87	9%	6,66	99.84	53
2	B (75:25)	29,3	28	4,64	29,44	0,95	7%	3,57	99.90	60
3	C (70:30)	32	30	6,66	38,86	0,77	9%	3,33	99.88	77
4	D (65:35)	39,8	38,2	7,21	47,73	0,8	7%	3,04	99.90	92
5	E (60:40)	47,5	45,1	9,53	52,32	0,86	8%	2,89	99.89	98

This study compared with previous studies that discussed the characteristics of briquettes from agricultural waste. A study conducted by Rashif et al. [35], the characteristics of briquettes from rice husk waste and corn cobs were measured using four parameters: water content, ash content, calorific value, and bound carbon. Corn cobs without polypropylene have a water content of 11.16%, ash content of 20.04%, fixed carbon content of 77.44%, and a calorific value of 5,156.93 calories per gram. The environmental impact is equivalent to an ecological cost of 0.387 US Dollars. In a study conducted by Tanko et.al [22] related to the characteristics of briquettes from rice husk waste and coconut shells measured using 4 parameters, namely water content, ash content, calorific value, and density, it was found that the comparison of the calorific value of the experimental and calculated briquettes showed that both were under the American Test Material Standard (ASTM). The calorific value of the five briquette ratios is not a function of water and ash content but rather the total carbon content. When compared between the three studies above per parameter with international standards, the percentage of ash content that meets the research of Rashief et al. with ash content below 8%. This shows that the material used in making briquettes still requires an optimal drying process by increasing the drying temperature or requiring a longer time. Another thing that can be done to reduce water content is adding plastic waste because plastic cannot absorb water [35].

3.1 Physical Properties

3.1.1 Moisture Content

The moisture content in briquettes is an important factor that affects combustion efficiency and overall performance as a fuel source. In the case of Sample E, consisting of 60% charcoal and 40% binder, the observed moisture content of 9.53% was significantly higher compared to other compositions. This increase in moisture content can be attributed to the nature of the binder used, as studies have shown that higher binder levels typically result in greater water retention [36]. The properties of the binder play an essential role in binding the materials together but also contribute to the briquettes' moisture content. Research shows that optimal moisture content is critical for achieving efficient combustion; lower moisture content generally improves ignition and increases calorific value, making briquettes more effective as an energy source [37].

The implications of moisture content on combustion efficiency are significant. Briquettes with high moisture content tend not to ignite well and burn incompletely, leading to lower energy output and higher emissions [27]. This relationship highlights the importance of careful formulation in briquette production, where balancing binder levels is key to minimizing water retention while maintaining structural integrity. For instance, research has shown that briquettes with moisture content below 10% exhibit superior combustion characteristics, including faster ignition times and higher calorific values [38]. Thus, optimizing the physical properties of briquettes, particularly their moisture content, is essential for improving their suitability as a renewable energy source. This emphasizes the need for ongoing research into binder formulations and processing techniques to produce high-quality briquettes that effectively meet energy demands while minimizing environmental impact.

3.1.2 Density

The density of briquettes is a vital parameter that significantly affects their mechanical strength and combustion performance. In this study, the briquettes showed a density range from 0.77 g/cm³ to 0.95 g/cm³, with Sample B (75% biomass and 25% binder) achieving the highest density of 0.95 g/cm³. This finding is consistent with existing literature, which indicates that the optimal density for biomass briquettes is usually between 0.8 g/cm³ and 1.2 g/cm³ [39]. Briquettes with higher density are generally associated with better structural integrity, improving their resistance to mechanical stress during handling and transport. Furthermore, increased density often correlates with better combustion characteristics, as denser briquettes tend to have a higher energy-to-volume ratio, facilitating more efficient heat generation during combustion [40].

The relationship between briquette density and combustion performance can be attributed to several factors, including the composition of raw materials and the pressing conditions used during production. Higher-density briquettes are usually produced under greater compaction pressure, resulting in more uniform particle distribution and reduced porosity [41]. This leads to better ignition properties and a more stable combustion process, as denser briquettes can maintain their structural integrity under high temperatures. Additionally, previous research has shown that briquettes with a density exceeding 1 g/cm³ often demonstrate higher calorific values and lower emissions during combustion [38]. Therefore, understanding the interaction between density and other physical properties is essential to optimize briquette formulations to maximize energy output while minimizing environmental impact.

More studies were conducted to measure the density of briquettes. The study found that the density value in various variations was 0.8 to 3.0 gr/cm^3 and had met the Indonesian Standard quality standards of at least 0.46 gr/cm3. The density of briquettes is influenced by the particle size of the raw materials, the type and concentration of adhesive, the pressure during manufacture, and the homogeneity of the mixture [42]. Smaller particles will increase the contact surface area, thereby increasing the density and bond strength between particles [43]. This study used a mixture of corn cobs and coconut shells as raw materials, which have more rigid material characteristics than rice husks. These two materials significantly affect the density results obtained from briquette products that have met Indonesian quality standards. The type of raw material affects the density; for example, coconut shell charcoal, which has a hard texture and strong bonds, can produce briquettes with a higher density compared to other raw materials [42].

3.1.3 Ash Content

The ash content of biomass briquettes is a critical factor affecting combustion efficiency and fuel quality. In this study, all samples exhibited very low ash content, with Sample B showing the lowest at 3.57%. This low ash content is advantageous, as it typically indicates higher fuel quality, leading to better combustion performance. Research consistently shows lower ash content in biomass fuels correlates with reduced operational issues, such as residue buildup and diminished calorific value [44].

High ash content can cause significant problems in combustion systems, including slagging and fouling, which reduce efficiency and increase maintenance costs [45]. Thus, the findings of this study align with previous literature emphasizing low ash content as a desirable characteristic for effective biomass fuels.

The benefits of low ash content are not limited to combustion efficiency; they also impact the sustainability of biomass energy systems. High-quality fuels with low ash content are crucial for minimizing environmental impacts, as they produce fewer emissions during combustion [26]. Conversely, fuels with high ash content can contribute to air pollution and other environmental issues due to the release of particulates and other pollutants. For instance, studies have shown that biomass with ash content below 5% is optimal for energy generation, ensuring higher calorific value and cleaner combustion characteristics [38]. As a result, this study's findings highlight the importance of controlling ash content in briquette production and reinforce the need for ongoing research to optimize biomass raw materials. This optimization aims to improve combustion properties while reducing environmental impacts.

The ash content parameter found that the current research has met the set quality standards, which is a maximum of 8%. The research conducted by Rashif et al. and Tank et al. has not met the SNI quality standards. Several factors, including the raw material used, influence ash content. Different raw materials have different chemical compositions and mineral content [46]. The higher the mineral content, such as potassium, magnesium, calcium, and silica, in the raw material, the higher the ash content of the briquettes [47]. The research conducted by Tanko et al. [2] found that the water content was relatively high, causing the ash content to be high. They found that high water content in raw materials can inhibit combustion and increase ash residue. In the research of Rashif et al. [35], it was found that adding plastic waste to the raw material mixture of briquettes can reduce their ash content. Only two studies were carried out to measure fixed carbon content. The results obtained from the study by Rashif et al. showed that several variations did not meet the Indonesian standard quality standards of a minimum of 77% [35]. Several factors affect bound carbon, one of which is that the raw material that contains more carbon will produce a higher bound carbon content [48], [49]. In addition, high ash content will reduce the bound carbon content and the calorific value of the briquettes [47], [50].

The study by Rashief et al. found that adding plastic waste to the mixture of raw materials can reduce the ash content of the briquettes. The measurement of fixed carbon content was only carried out in two studies. The results obtained from the study conducted by Rashief et al. showed several variations that did not meet the Indonesian standard quality standards, which were a minimum of 77%. Several factors affect bound carbon, one of which is that the raw material that contains more carbon will produce a higher bound carbon content. In addition, high ash content will reduce the bound carbon content and the calorific value of the briquettes [47], [49], [50]. In the measurement of calorific value, it was found that from the three studies conducted, several samples did not meet the Indonesian Standard quality standards, which were a minimum of 5000 (Cal/gr). Testing the calorific value of all combinations in the three studies produced values between 2374.01 and 6414.48. In the study by Senchi et al., it was stated that the calorific value of corn cobs had a higher calorific value compared to rice husks; this means that corn cobs have characteristics that are more flammable than rice husks [51]. The factors that influence the calorific value are water content and ash content. The higher the water content in the briquette, the lower the calorific value because of the energy needed to evaporate the water. High ash content can reduce the calorific value because the ash does not burn and reduces the amount of energy produced [52]–[55].

3.2 Mechanical Properties

3.2.1 Combustion Performance

The burning time of biomass briquettes plays a crucial role in determining their efficiency and suitability for various applications, particularly heating and cooking. In this study, the observed burning time ranged from 53 minutes for Sample A to 98 minutes for Sample E, demonstrating a clear trend where increased binder content correlates with longer burning durations. Specifically, Sample B, which contained a higher binder ratio, exhibited superior combustion characteristics, including longer burning times and a more stable flame. This stability is critical for practical applications as it ensures consistent heat output and reduces the need for frequent refueling [56]. These findings align with previous studies indicating that binder addition enhances the structural integrity of briquettes and improves combustion performance by promoting more uniform burning [57].

The underlying reason for the increased burning time with higher binder ratios can be attributed to the binder's role in improving fuel density and encouraging better particle cohesion within the briquettes. The binder effectively binds biomass particles together, reducing porosity and enhancing heat retention during combustion [36]. This results in more efficient fuel that burns slower and more steadily. Additionally, the stable flame produced by briquettes with higher binder content is particularly valuable for practical applications, providing reliable heat without fluctuations that could complicate cooking or heating processes [37].

The combustion performance tests conducted in this study corroborate these findings, showing that briquettes with higher binder ratios not only burned longer but also produced a flame less prone to flickering or extinguishing. Therefore, optimizing binder content in briquette formulations is essential to enhance performance and user experience in energy applications.

3.2.2 Volatile Matter Content

The volatile matter content in biomass briquettes is a critical determinant of their ignition efficiency and combustion performance. In this study, the volatile matter content across all samples was relatively consistent, ranging from 7% to 9%. This consistency indicates that all samples possess adequate characteristics for effective combustion, as volatile matter facilitates ignition. Previous studies have shown that higher volatile matter content can enhance ignition properties and improve combustion performance [58]. The presence of volatile compounds allows for the rapid release of gases during combustion, which is crucial for sustaining a flame and optimizing energy output. Thus, the values observed in this study suggest that the briquettes are highly suitable for practical applications in heating and cooking.

Moreover, the relationship between volatile matter and combustion performance is well-documented, highlighting a dual effect: while higher volatile matter content can improve ignition and initial burning rates, it can also result in faster-burning rates, potentially compromising fuel efficiency over time [59]. This phenomenon is particularly relevant in applications requiring sustained heat generation. For instance, briquettes with excessive volatile matter content may burn too quickly, leading to rapid fuel consumption and potentially higher emissions [60].

Therefore, while the observed levels of volatile matter indicate adequate combustion characteristics, it is essential to balance this property with other factors, such as fixed carbon content, to ensure optimal combustion stability and efficiency. These findings underscore the importance of formulating briquettes with the appropriate volatile matter ratio to achieve desired performance outcomes in energy applications.

3.2.3 Carbon Content

The percentage of fixed carbon observed in the briquettes was remarkably high, exceeding 99% in most samples. This high carbon content indicates high-quality charcoal, essential for energy production during combustion. The significance of carbon content in solid fuels cannot be overstated, as it directly correlates with calorific value and overall fuel performance. Research consistently shows that higher carbon content increases energy output, as carbon is the primary component responsible for heat generation during combustion [61]. Specifically, the high fixed carbon content observed in these briquettes suggests substantial energy production upon burning, aligning with findings from other studies that emphasize the importance of carbon content in determining the efficiency and effectiveness of biomass fuels [62].

Furthermore, the relationship between high carbon content and increased calorific value is well-documented. For instance, charcoal typically exhibits significantly higher calorific values than raw biomass due to its concentrated carbon content and reduced volatile matter [63]. High-carbon fuels also tend to perform better during combustion, producing less smoke and fewer emissions than low-carbon alternatives [45]. This is particularly relevant in contexts where air quality and environmental impact are critical considerations.

The findings of this study not only highlight the potential of these briquettes as a viable energy source and reinforce the need to optimize carbon content during the production process to enhance fuel quality and performance further. Maintaining a high carbon percentage in briquette formulations is crucial to maximizing their utility as an efficient and sustainable energy source.

3.3 Statistical Analysis of Briquette Properties

3.3.1 Result Data

This study comprehensively measures various physical and mechanical properties of biochar briquettes, including moisture content, density, ash content, volatile matter content, carbon content, and burning time. These parameters are crucial for evaluating the quality and performance of briquettes as a renewable energy source. The statistical methods applied to analyze these parameters across different briquette compositions (ranging from Sample A with an 80:20 ratio to Sample E with a 60:40 ratio) enabled robust comparisons of how composition variations affect briquette characteristics. Previous research has established that moisture content and density significantly influence combustion efficiency and fuel quality [39]. This study identified trends and correlations among physical properties using statistical analysis, offering insights into how different formulations can optimize performance.

The results from this analysis indicate that the briquettes possess adequate characteristics for effective combustion. For instance, the consistent volatile matter content across all samples demonstrates that all formulations can achieve good ignition properties, which are essential for practical applications in heating and cooking. The high carbon content, exceeding 99% in most samples, further supports their quality as it directly correlates with increased calorific value [64]. Additionally, the low ash content across all samples minimizes operational issues such as residue buildup during combustion [45]. These findings align with previous research emphasizing the importance of maintaining optimal physical properties in briquette production to enhance combustion efficiency and overall fuel performance [63]. Thus, this study reinforces existing knowledge and contributes valuable data that can guide future research and development of biomass energy solutions.

3.3.2 Key Findings

a. Moisture Content

The moisture content of biomass briquettes is a critical parameter that significantly impacts combustion efficiency and overall fuel quality. In this study, the moisture content ranged from 4% to 9.53%, demonstrating a clear trend where higher binder ratios correlated with increased moisture retention. This observation aligns with previous research emphasizing the importance of maintaining low moisture levels for optimal combustion performance [39]. High moisture content can hinder ignition and reduce the calorific value of briquettes, as energy is wasted on evaporating water before combustion can occur [64]. Consequently, briquettes with lower moisture content are generally preferred, as they are easier to ignite and burn more efficiently, maximizing heat output while minimizing emissions.

The relationship between binder content and moisture retention can be attributed to the inherent properties of binders, which can increase the briquettes' ability to retain moisture. As noted in previous studies, while binders are essential for binding biomass particles, they can also contribute to higher water absorption, leading to increased moisture content [40]. The findings of this study highlight the need for careful briquette formulation to balance binder usage while ensuring that moisture levels remain within acceptable limits. For instance, research suggests that the optimal moisture content for biomass fuels should ideally be below 10% to ensure efficient combustion [39].

Thus, controlling moisture content through proper drying methods and binder selection is critical for producing high-quality briquettes that perform well in practical applications such as heating and cooking. This study underscores the importance of optimizing physical properties in briquette production to enhance their suitability as a renewable energy source.

b. Density

The density of biomass briquettes is an important factor influencing their mechanical strength and combustion performance. In this study, the briquette density ranged from 0.77 g/cm³ to 0.95 g/cm³, with Sample B exhibiting the highest density at 0.95 g/cm³, indicating superior mechanical strength. This finding is significant because higher-density briquettes are generally associated with better structural integrity, enhancing their resistance to mechanical stress during handling and transportation [39]. This aligns with previous research that has established a direct relationship between binder content and briquette density, showing that an optimal binder ratio can improve compaction processes and enhance overall briquette quality [65].

The implications of these findings extend beyond physical properties; they also influence the combustion characteristics of the briquettes. Higher-density briquettes typically demonstrate improved combustion efficiency due to reduced porosity and increased heat retention during burning [39]. This is particularly important for practical applications such as heating and cooking, where consistent and efficient fuel performance is desired. Furthermore, these results emphasize the importance of carefully selecting the binder ratio in briquette formulations to achieve the desired density while maintaining other critical properties such as moisture content and ash content [60]. By optimizing these parameters, producers can manufacture high-quality biomass briquettes that meet energy demands and minimize the environmental impact associated with combustion. Therefore, this study provides valuable insights into the formulation and production processes of biomass briquettes, aiming to enhance their performance as a sustainable energy source.

c. Burning Time

The burning time of biomass briquettes is a crucial factor influencing their utility as a renewable energy source. In this study, burning times ranged from 53 minutes for Sample A to 98 minutes for Sample E, indicating significant variation across different briquette compositions. Statistical analysis confirmed a significant correlation between burning time, density, and binder content. Higher-density briquettes, often produced with increased binder ratios, tended to burn longer due to enhanced structural integrity and heat retention capabilities [60]. These findings align with previous research highlighting the role of binders in improving the mechanical properties of briquettes, which in turn affects their combustion characteristics [57]. The increased burning time observed in samples with higher binder content demonstrates that these briquettes maintain their shape during combustion and provide more sustainable heat output, making them particularly suitable for applications such as cooking and heating.

The correlation between binder content and burning time can be attributed to the role of binders in binding biomass particles, which enhances briquette density and reduces porosity. The higher binder concentrations result in better compaction and cohesion among particles, leading to slower combustion rates and longer burning durations. This is critical, as while higher volatile matter can improve ignition, it may also lead to faster-burning rates, potentially compromising fuel efficiency [56].

Therefore, optimizing binder content is essential to balance ignition properties and sustained combustion. The findings of this study underscore the importance of formulating briquettes with the right binder ratios to enhance performance and user experience in energy applications. By understanding this relationship, producers can develop biomass briquettes that maximize energy output while minimizing environmental impacts associated with combustion.

3.4 Implications for Renewable Energy

The statistical significance of the findings regarding biochar briquettes demonstrates that optimizing their composition can significantly enhance their performance as a renewable energy source. This study highlights that variations in the ratio of biomass feedstock to binder directly affect key properties such as density, burning time, and calorific value. For instance, incorporating organic binders in higher proportions, such as cassava or banana peel, not only improves the structural integrity of briquettes but also enhances their combustion efficiency by promoting more stable burning characteristics. These findings align with existing literature emphasizing the importance of formulating briquettes with optimal compositions to achieve desired physical and thermal properties [66]. By refining these compositions, producers can create high-quality briquettes that deliver sustainable energy output while minimizing environmental impact.

Furthermore, the utilization of agricultural waste for briquette production addresses significant waste management challenges while contributing to the circular economy. Converting agricultural residues into biochar and briquettes not only provides an alternative fuel source but also mitigates issues associated with waste disposal, such as open burning and landfill overflow. This process transforms waste into a valuable resource, thereby reducing greenhouse gas emissions and promoting sustainability [45]. The environmental benefits of this approach are substantial; recycling organic waste into energy products helps communities reduce their reliance on fossil fuels and lower their carbon footprint. In summary, optimizing the composition of biochar briquettes not only improves their performance as a renewable energy source but also supports broader environmental goals by fostering sustainable practices in waste management and energy production.

3.5 Environmental Impact and Sustainability

3.5.1 Renewable Energy Potential

Biomass briquettes derived from agricultural waste represent a sustainable energy solution that addresses various environmental challenges. As highlighted by experts in the field, these briquettes reduce dependence on fossil fuels, thereby contributing to lower greenhouse gas emissions during combustion compared to traditional fuels. This transition is crucial in the context of global efforts to combat climate change, as fossil fuels are a major source of greenhouse gas emissions. Biomass briquettes, being carbon-neutral, release carbon dioxide offset by the carbon absorbed during biomass growth, making them an environmentally friendly alternative [67]. The production and use of these briquettes not only help reduce carbon footprints but also promote the utilization of agricultural residues that would otherwise decompose and contribute to methane emissions[45].

Furthermore, the potential of biomass briquettes to serve as an alternative energy source aligns with global initiatives aimed at transitioning to renewable energy systems. More countries are increasingly adopting biomass briquettes as part of their national strategies to enhance energy resilience while reducing carbon emissions. This shift to renewable resources not only addresses energy needs but also stimulates local economies by creating jobs in briquette production and promoting sustainable agricultural practices. Moreover, the modular nature of briquette production allows for localized energy solutions, increasing resilience to external shocks associated with fossil fuel markets [68]. As such, biomass briquettes not only contribute to the circular economy by transforming waste into energy but also play a critical role in driving sustainable development and environmental stewardship on a global scale.

3.5.2 Carbon Sequestration

Biochar plays a crucial role in carbon sequestration, offering dual benefits of enhancing energy production while mitigating climate change. Numerous studies have demonstrated that biochar can effectively sequester carbon in soil, contributing to long-term carbon storage and reducing atmospheric CO_2 levels [69]. The production of biochar involves the pyrolysis of organic materials, converting biomass into a stable carbon form that can persist in soil for hundreds to thousands of years [70]. This stability is critical, as it prevents the rapid release of carbon back into the atmosphere, which would occur if organic materials decomposed naturally. The high carbon content observed in the briquettes further supports this potential, as it indicates that these materials can not only serve as energy sources but also act as effective carbon sinks when applied to agricultural soils [71]. Biochar's ability to enhance soil health by improving nutrient retention and water-holding capacity reinforces its role in sustainable agriculture, making it a valuable tool for climate change mitigation and food security.

The implications of biochar's carbon sequestration capabilities extend beyond environmental benefits; they also align with global efforts to transition to renewable energy systems. By utilizing agricultural waste to produce biochar, we can address waste management challenges while providing a sustainable energy source. This approach not only reduces reliance on fossil fuels but also cuts greenhouse gas emissions associated with traditional waste disposal methods, such as open burning or landfilling [45]. Furthermore, integrating biochar into agricultural practices can boost crop yields and resilience to climate variability, supporting rural economies and promoting sustainable development [71]. As countries seek innovative solutions to combat climate change and promote sustainability, the adoption of biochar technology offers a promising pathway that leverages waste resources for both environmental and economic benefits.

3.5.3 Waste Management

The utilization of agricultural waste for briquette production offers a sustainable solution for energy generation and waste management, significantly reducing contributions to landfills and associated methane emissions. This approach aligns with findings from various studies indicating that biomass briquette production provides a more sustainable way to manage organic waste [72]. Agricultural residues, such as straw, husks, and other by-products, often end up in landfills or are burned, releasing methane—a potent greenhouse gas—into the atmosphere. By converting these materials into briquettes, we not only provide a renewable energy source but also mitigate the environmental impact of waste disposal methods. The briquetting process compresses organic waste into dense blocks, making it easier to transport and store while enhancing its energy content [73]. This transformation is crucial in addressing the dual challenges of energy security and environmental sustainability.

Moreover, biomass briquette production contributes to the circular economy by turning waste into valuable resources. This aligns with global efforts to promote sustainable practices that reduce reliance on fossil fuels and lower greenhouse gas emissions. The carbon-neutral nature of biomass briquettes is particularly significant; during combustion, the carbon released is offset by the carbon absorbed during the biomass growth cycle, making them a sustainable alternative to traditional fuels. Additionally, the use of agricultural waste not only addresses waste management issues but also supports rural economies by creating local jobs in briquette production and distribution [4]. As countries seek innovative solutions to combat climate change and enhance energy resilience, biomass briquettes offer a promising pathway that leverages agricultural waste for environmental and economic benefits. This approach not only aids in managing organic waste sustainably but also drives the transition toward renewable energy systems, which are critical for a sustainable future.

3.6 Statistical Considerations for Future Research

3.6.1 Data Collection and Analysis

The exploration of agricultural waste as a source for briquette production has gained significant attention due to its potential to provide sustainable energy solutions while addressing waste management challenges [74]. Statistical observations highlighting the need for larger sample sizes and a more diverse range of agricultural waste types in future research are crucial. Recent studies, such as those examining briquettes made from cassava stems and bamboo charcoal, have demonstrated promising results, including high calorific values and strong mechanical properties [75]. However, the robustness of these findings could be enhanced by incorporating a broader spectrum of agricultural residues and increasing sample sizes. This approach would not only improve the statistical validity of results but also facilitate a more comprehensive understanding of how different biomass types interact during the briquette-making process.

The application of multivariate analysis could significantly deepen insights into the complex relationships between briquette properties and their performance metrics. For example, factors such as moisture content, ash content, and particle size variation (0.75–4.8 mm) can influence combustion efficiency and emissions [75]. By employing advanced statistical techniques, researchers can identify optimal combinations of materials that yield briquettes with superior performance characteristics. Such analyses could reveal interactions that are not apparent through univariate methods, ultimately leading to the development of higher-quality briquettes that meet both economic and environmental standards. As various studies have shown, the potential for these materials to serve as viable alternatives to traditional fuels is substantial [74]. Therefore, future research should prioritize methodological rigor and diversity in sample selection to fully capitalize on the benefits of agricultural waste in briquette production.

3.6.2 Long-Term Studies

Long-term studies examining the performance of biochar briquettes in real-world conditions are crucial for validating laboratory findings and understanding their practical applications. Laboratory tests often provide controlled environments that may not accurately reflect the complexities of actual usage scenarios, such as variations in humidity, temperature, and user handling. By conducting extensive field studies, researchers can evaluate the durability, combustion efficiency, and overall performance of these briquettes in diverse settings. Such empirical evaluations are essential as they may reveal potential issues overlooked in laboratory tests, such as the impact of environmental factors on briquette integrity and combustion characteristics [76]. For instance, studies have shown that briquettes can achieve densities exceeding 1330 kg/m³ with calorific values over 17 MJ/kg, indicating that certain agricultural residues can be optimized for better performance in real-world applications [75].

Furthermore, long-term studies can provide insights into the economic feasibility of producing and using biochar briquettes on a large scale. Economic assessments are vital for determining the viability of transitioning from traditional fuels to biochar alternatives. Research has shown that projects utilizing agricultural waste for briquette production can be profitable, with favorable internal rates of return and payback periods [74]. By analyzing production costs, market demand, and potential savings from reduced dependence on fossil fuels, stakeholders can make informed decisions about investing in biochar technology. Additionally, understanding the economic landscape will help policymakers develop supportive frameworks that encourage sustainable energy practices. In summary, integrating long-term performance studies with economic analysis will not only validate laboratory results but also pave the way for broader adoption of biochar briquettes as a sustainable energy source.

4. Conclusion

This study demonstrates the potential of biochar briquettes derived from agricultural waste as an efficient and sustainable energy source. By optimizing key parameters such as moisture content, density, ash content, and calorific value, the findings show that an optimal biomass-to-binder ratio can significantly enhance fuel quality, achieving a high calorific value (7,192 kcal/kg) and low ash content (3.57%). These characteristics contribute to improved combustion efficiency, reduced emissions, and enhanced sustainability.

Beyond laboratory-scale research, the results hold significant implications for industrial and large-scale applications. Biochar briquettes offer a cost-effective and eco-friendly alternative to conventional fuels, particularly in rural communities, small-scale industries, and power generation sectors. The economic viability of large-scale production depends on factors such as raw material availability, production costs, and supply chain efficiency. Policies supporting renewable energy adoption and incentives for waste-to-energy technologies could further enhance the feasibility of widespread implementation.

Future research should focus on scaling up production processes, assessing long-term combustion performance, and optimizing binder formulations for enhanced durability and energy output. Additionally, life cycle assessments and economic feasibility studies are essential to evaluate the broader impact of biochar briquettes on energy markets and environmental sustainability. As the global transition toward clean energy accelerates, biochar briquettes present a promising, low-emission alternative that supports carbon sequestration, circular economy principles, and energy security.

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