

Effect of Binder Concentration on Density and Combustion Performance of Sawdust Biopellets

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ABSTRACT

Sawdust is an abundant by-product of the wood processing industry with strong potential as a raw material for biopellet production. However, the quality and combustion performance of biopellets are significantly influenced by binder concentration. This study investigates the effect of binder concentration (35%, 40%, and 45%) on the density and combustion performance of sawdust-based biopellets. The pellets were characterized in terms of density, calorific value, burning rate, and ignition behavior. The results show that increasing binder concentration enhances pellet density from 1.16 ± 0.02 to 1.26 ± 0.01 g/cm³, indicating improved structural compactness and reduced porosity. However, the calorific value decreases from 14.47 ± 0.13 to 12.23 ± 0.13 MJ/kg due to both physical dilution and the lower carbon content of the binder material. Combustion analysis reveals that higher binder content increases ignition time and prolongs burning duration, primarily due to restricted oxygen diffusion within the denser pellet structure. The burning rate ranged from 23.96 to 25.27 g/min, indicating relatively stable mass consumption despite variations in combustion time. Overall, the results demonstrate a trade off between mechanical strength and energy performance. A binder concentration of 35% provides the highest energy efficiency, while higher concentrations improve structural durability but reduce combustion reactivity. These findings highlight the importance of optimizing binder content to achieve balanced performance in biomass-based solid fuels.

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Introduction

The increasing global demand for energy, driven by population growth and industrial development, has intensified the need for sustainable and environmentally friendly energy sources. The continued dependence on fossil fuels has raised serious concerns due to the depletion of natural reserves and the environmental impacts associated with greenhouse gas emissions. These challenges have encouraged the exploration of renewable energy resources that are capable of supporting long-term energy sustainability. Among the available renewable resources, biomass has gained significant attention due to its

abundance, renewability, and potential to be converted into various forms of energy [1,2].

Biomass can be utilized as an energy source through several conversion pathways, including thermochemical, biochemical, and mechanical processes. One of the most practical approaches is the production of solid biofuels such as briquettes and biopellets. Biopellets are produced through a densification process in which fine biomass particles are compressed under pressure to form compact cylindrical pellets. This process significantly improves the physical properties of raw biomass, including bulk density, energy density, and storage stability, making biopellets easier to handle, transport, and utilize as a renewable fuel [3,4].

Among various biomass residues, sawdust is considered a promising raw material for pellet production. Sawdust is widely generated as a by-product of wood processing industries such as sawmills, furniture manufacturing, and carpentry activities. In many regions, this biomass residue is produced in large quantities and remains underutilized. If not properly managed, sawdust waste may accumulate and contribute to environmental problems. Converting sawdust into biopellets therefore provides an effective approach to utilize biomass waste while simultaneously producing a renewable energy resource [5,6].

The quality of biopellets produced from biomass is influenced by several factors during the pelletization process. Important parameters include particle size, moisture content, compaction pressure, and the addition of binding agents. Binders are commonly used to improve the adhesion between biomass particles, resulting in pellets with higher density and better mechanical strength. The appropriate use of binders can enhance pellet durability and stability during storage and transportation [7].

Binder concentration is an important parameter that may influence both the physical properties and combustion performance of biopellets. Variations in binder concentration can affect pellet density, structural integrity, and combustion characteristics such as calorific value and burning behavior. However, many previous studies have focused mainly on individual parameters, such as pellet density or calorific value, while fewer studies have evaluated multiple combustion-related characteristics simultaneously, particularly in sawdust-based biopellets [8,9].

Therefore, this study aims to investigate the effect of binder concentration on the physical properties and combustion performance of sawdust biopellets. In this study, three different binder concentrations 35%, 40%, and 45% were applied during pellet production. The produced pellets were characterized in terms of density, calorific value, burning rate, and flame characteristics. The hypothesis of this study is that variations in binder concentration influence the density and combustion behavior of sawdust biopellets,

thereby affecting their overall fuel performance [10].

Materials and Methods

1. Materials

The primary raw material used in this study was sawdust obtained from a local wood processing workshop. The collected sawdust was first cleaned to remove impurities such as small wood chips, dust, and other contaminants. After cleaning, the sawdust was air-dried to reduce its moisture content before being used in the pelletization process.

A binder material was used to improve the bonding between sawdust particles during pellet formation. The binder was prepared in three different concentrations, namely 35%, 40%, and 45% of the total mixture. These variations were selected to evaluate the influence of binder concentration on the physical and combustion characteristics of the produced biopellets.

The materials used in this research consisted of sawdust as the main biomass feedstock, binder solution, and distilled water when necessary for mixture preparation.

2. Preparation of Sawdust

The collected sawdust was first dried under ambient conditions to reduce its moisture content and ensure consistent pellet formation. After drying, the sawdust was sieved to obtain a more uniform particle size and to remove oversized particles. The prepared sawdust was then stored in sealed containers prior to the pelletization process to prevent moisture absorption from the surrounding environment.

3. Biopellet Production

Biopellets were produced through a densification process using a manual pellet press. The prepared sawdust was mixed with binder according to the predetermined concentrations of 35%, 40%, and 45%. The mixture was stirred thoroughly until a homogeneous blend was obtained to ensure uniform distribution of the binder throughout the biomass particles.

After mixing, the prepared biomass mixture was inserted into the pellet mold and compressed using the pellet press to form

cylindrical pellets. The formed pellets were then removed from the mold and dried under ambient conditions until a stable structure was obtained. The drying process was necessary to reduce excess moisture and improve pellet strength before further testing.

4. Density Test

The density of the produced biopellets was determined by measuring the mass and volume of each pellet. The mass of the pellets was measured using a digital analytical balance, while the dimensions (diameter and length) were measured using a vernier caliper. Pellet density was calculated using the following equation:

$$\text{Density} = \frac{\text{Mass}}{\text{Volume}} \quad (1)$$

where density is expressed in g/cm³, mass is the weight of the pellet (g), and volume is the pellet volume (cm³). Density measurements were conducted for several pellets from each binder concentration treatment, and the average value was reported.

5. Calorific Value Analysis

The calorific value of the produced biopellets was determined to evaluate their energy content. The analysis was conducted using a bomb calorimeter. A small amount of pellet sample was placed in the combustion chamber of the calorimeter and completely burned in the presence of oxygen. The heat released during the combustion process was measured and used to calculate the calorific value of the pellet sample. The calorific value was expressed in kcal/kg.

6. Burning Rate Test

The burning rate test was conducted to determine the combustion behavior of the biopellets. A single pellet sample was ignited under controlled conditions and allowed to burn completely. The initial mass of the pellet was measured before combustion, and the total combustion time was recorded using a stopwatch.

The burning rate was calculated using the following equation:

$$\text{Burning Rate} = \frac{\text{Initial Mass}}{\text{Combustion Time}} \quad (1)$$

The burning rate was expressed in g/min. Each test was repeated several times to ensure the reliability of the data.

7. Flame Characteristics Observation

The flame characteristics of the biopellets were observed during the combustion process. The observations focused on flame stability, flame color, and combustion behavior. Visual observation was conducted during the burning process to identify differences in flame characteristics among pellets produced with different binder concentrations.

All experiments were conducted in triplicate, and the results are presented as mean $\pm$ standard deviation.

Results and Discussion

1. Effect of Binder Concentration on Biopellet Density

Pellet density is one of the most important physical properties influencing the storage, transportation, and combustion performance of biomass fuels. Higher pellet density generally indicates better mechanical strength and improved energy content per unit volume.

The results of the density measurements for sawdust biopellets with binder concentrations of 35%, 40%, and 45% are presented in Table 1.

Table 1. Density of Sawdust biopellets at different binder concentrations

Binder Concentration (%)	Average Mass (g)	Average volume (cm ³)	Density (g/cm ³)
35	70	60.2	1.16 $\pm$ 0.02
40	75	61.5	1.21 $\pm$ 0.02
45	80	63	1.26 $\pm$ 0.01

The density of the produced biopellets increased with increasing binder concentration, ranging from 1.16 $\pm$ 0.02 to 1.26 $\pm$ 0.01 g/cm³. The relatively low standard deviation values indicate good repeatability and consistency of the pelletization process. Higher binder content improved interparticle bonding and reduced void spaces, resulting in a more compact

structure with lower porosity. To better illustrate the relationship between binder concentration and pellet density, the experimental results are also presented in Figure 1.

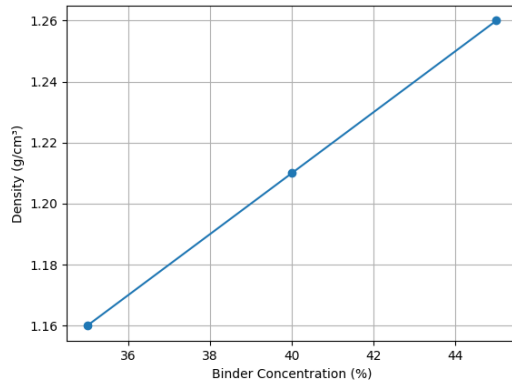


Figure 1. Effect of binder concentration on pellet density

Based on the experimental results, the density of the produced biopellets increased with increasing binder concentration. The pellets produced with a binder concentration of 45% showed the highest density among all treatments. This trend can be explained by the improved bonding between biomass particles when a higher proportion of binder is present. The binder fills the void spaces between sawdust particles, resulting in a more compact pellet structure.

Similar observations were reported by Saidur Rahman Khan and colleagues, who found that binder addition can significantly improve pellet density and mechanical stability in biomass densification processes. In addition, studies by Jing Liu also indicated that higher binder content contributes to better particle adhesion and reduced porosity in biomass pellets [11].

These findings suggest that binder concentration plays a critical role in determining the structural integrity of biopellets. However, excessive binder addition may not always be desirable because it can influence other combustion properties such as calorific value and burning characteristics. Therefore, identifying the optimal binder concentration is essential for achieving balanced physical and combustion properties [12-14].

2. Calorific Value of Sawdust Biopellets

The calorific value represents the amount of energy released during the complete combustion of fuel. It is an important parameter for evaluating the energy potential of biomass-based fuels such as biopellets.

The measured calorific values of the biopellets produced with different binder concentrations are presented in Table 2.

Table 2. Calorific value of sawdust biopellets

Binder Concentration (%)	Calorific Value (MJ/Kg)
35	14.47 ± 0.13
40	12.67 ± 0.13
45	12.23 ± 0.13

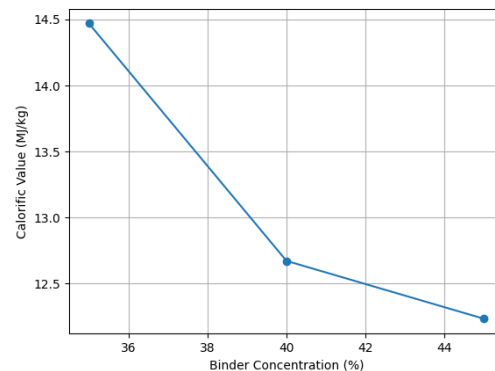


Figure 2. Effect of binder concentration on calorific value

The relatively small standard deviation (± 0.13 MJ/kg) suggests that the calorific value measurements are reliable and reproducible. The variation of calorific value with binder concentration is further illustrated in Figure 2. The decrease in calorific value with increasing binder concentration can also be explained by the chemical nature of the binder material. Most binders used in biomass pelletization, such as starch-based or water-based binders, contain lower carbon content and higher oxygen content compared to lignocellulosic biomass. This chemical composition reduces the overall fixed carbon fraction and energy density of the pellets. Additionally, binders tend to promote the formation of more volatile compounds rather than fixed carbon during combustion, which contributes to lower heating values. Therefore, the dilution effect is not only physical

but also chemical in nature, directly influencing the energy performance of the biopellets [12,13].

The experimental results (Figure 2) show that binder concentration influenced the calorific value of the produced pellets. In general, changes in binder proportion altered the overall composition of the pellet mixture, which subsequently affected the energy content of the fuel. The obtained calorific values (12.23–14.47 MJ/kg) are within the typical range reported for sawdust-based biopellets. Previous studies have reported calorific values ranging from 13 to 18 MJ/kg depending on biomass composition and processing conditions. The slightly lower values observed at higher binder concentrations in this study further confirm the dilution effect of non-combustible components introduced by the binder. Biomass pellets with lower moisture and higher fixed carbon content typically exhibit higher calorific values. The calorific value of biomass fuels is strongly influenced by their chemical composition, including carbon, hydrogen, and lignin content [10].

Furthermore, research by M. Kaliyan demonstrated that binder type and concentration can modify the thermal characteristics of biomass pellets. Excessive binder addition may dilute the combustible biomass fraction, potentially reducing the overall calorific value of the pellets [12].

These results indicate that while binder improves pellet structure, its concentration must be carefully controlled to maintain optimal energy content.

3. Burning Rate Characteristics

The observed decrease in burning rate with increasing binder concentration is closely related to changes in internal pellet structure, particularly porosity and oxygen diffusion. Higher binder content leads to a denser and more compact structure with reduced pore volume. This reduction in porosity limits oxygen penetration into the pellet during combustion, thereby slowing down the oxidation process. Consequently, oxygen diffusion becomes the controlling factor in combustion kinetics. Pellets with lower porosity exhibit slower burning rates and longer combustion duration due to restricted airflow

within the structure. This finding highlights the strong interdependence between density, porosity, and combustion behavior in biomass pellets. Burning rate is an important indicator of combustion performance, as it reflects how quickly the fuel is consumed during combustion. A suitable burning rate ensures stable heat release and efficient fuel utilization.

The experimental results for the burning rate of sawdust biopellets are shown in **Table 3**. The burning rate of the biopellets ranged from 23.96 ± 0.48 to 25.27 ± 0.52 g/min. The relatively low standard deviation values indicate consistent combustion behavior across repeated tests. Although the total burning time increased with higher binder concentration, the burning rate remained within a narrow range, suggesting that mass consumption during combustion was relatively stable. However, pellets with higher density exhibited slightly lower burning rates, which can be attributed to reduced porosity and limited oxygen diffusion within the pellet structure.

Table 3. Burning rate of sawdust biopellets

Binder Concentration (%)	Burning time (minutes)	Burning rate (g/min)
35	2.77	25.27 ± 0.52
40	3.13	23.96 ± 0.48
45	3.20	25.00 ± 0.55

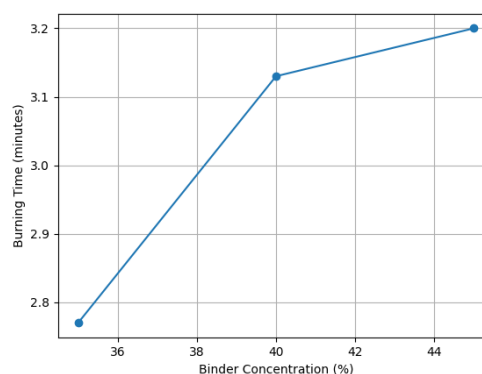


Figure 3. Effect of binder concentration on burning rate

The ignition time increased with binder concentration, which is consistent with the observed increase in density and reduction in porosity. Denser pellets require more time to reach ignition temperature due to limited oxygen diffusion and heat transfer within the

structure. The relationship between binder concentration and burning rate is illustrated in Figure 3.

The results indicate that binder concentration influenced the burning behavior of the pellets. Pellets with higher density generally burned more slowly due to the reduced internal porosity and limited oxygen diffusion within the pellet structure. Densified biomass fuels with higher compactness tend to exhibit slower combustion rates due to reduced air penetration. Pellet density and internal structure significantly affect combustion kinetics and burning duration. That optimizing binder concentration can help control the combustion rate of biopellets, which is important for improving their performance as a solid biofuel [14, 15].

4. Flame Characteristics

Flame characteristics provide qualitative information about the combustion efficiency and stability of biomass fuels. During the combustion test, the flame color, flame stability, and burning behavior of the biopellets were visually observed.

Representative observations of flame characteristics for each binder concentration are summarized in Table 4.

Binder Concentration (%)	Flame
35	orange
40	orange
45	orange

The yellow-orange flame observed in all samples indicates the presence of luminous combustion (Figure 4), typically associated with incomplete combustion of volatile compounds and soot particle formation. However, the relatively stable flame suggests a consistent release of combustible gases. Pellets with higher density tend to produce a more uniform flame due to controlled volatile release, which can improve combustion stability but may reduce instantaneous combustion efficiency. Therefore, flame characteristics in this study reflect a balance between combustion stability and efficiency.

Stable flames during biomass combustion indicate efficient oxidation of volatile gases released from the fuel. In addition, the stability of the flame observed in this study suggests that the pellet structure allowed continuous release of combustible gases during burning. Pellets with higher density tended to burn more steadily because their compact structure slowed the release of volatile compounds [16, 17].

These findings demonstrate that binder concentration not only affects physical properties but also influences combustion characteristics, including flame behavior. Binder concentration plays a significant role in determining pellet quality and combustion performance [18, 19].

Author Contribution

SF - Conceptualization, methodology design, investigation, data curation, formal analysis, writing. **SP** - Validation, and writing-original draft. **A** – Writing, review and editing; **VDA**: Data curation, and formal analysis.

Conclusion

This study demonstrates that binder concentration significantly influences both the physical and combustion properties of sawdust biopellets. Increasing binder concentration from 35% to 45% improved pellet density from 1.16 ± 0.02 to 1.26 ± 0.01 g/cm³, indicating enhanced structural compactness. However, this improvement was accompanied by a decrease in calorific value from 14.47 ± 0.13 to 12.23 ± 0.13 MJ/kg, representing a reduction of approximately 15.5% in energy content. In terms of combustion behavior, higher binder concentrations increased ignition time and prolonged burning duration due to reduced porosity and limited oxygen diffusion within the pellet structure. The burning rate remained relatively stable in the range of 23.96–25.27 g/min, indicating that mass consumption was not significantly affected despite changes in combustion dynamics.

Overall, the results confirm a clear trade-off between mechanical strength and energy performance. Among the tested formulations, the 35% binder concentration provides the most optimal balance, offering the highest calorific value and more reactive combustion behavior.

Therefore, this composition is recommended for energy oriented applications, while higher binder concentrations may be more suitable for applications requiring greater structural durability.

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