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The Effect of Different Waste Material Binders in Relation to *Khaya Senegalensis* Solid Fuel Pellet Quality

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ABSTRACT

Fuel pellets are an attractive renewable energy source derived from biomass sources thanks to their uniformity and ease of handling. However, raw biomass and waste material binders have several drawbacks, which include poor physical properties, particularly low density and compositional heterogeneity, which restrict their wider use as a general source of energy. Besides, due to the low energy density, low bulk density, and uneven shape and size of raw biomass, it is very difficult to store and transport biomass in its original form, which decreases transport efficiency. This study investigated the effect of waste material binders (rice husk, corn cob, and sugarcane bagasse) on the mechanical and thermal properties of Khaya Senagalensis pellets. The mechanical and thermal properties were determined according to ASTM standards. Waste material binders have affected pellet quality such as density, bulk density, moisture content, durability, compressive strength, shatter index, water resistance, ash content, volatile matter, fixed carbon, and calorific value. From the analysis, sugarcane bagasse as a binder shows the highest quality pellet in terms of mechanical properties. Sugarcane bagasse produces the highest density (0.967g/cm3), bulk density (0.4094), durability (99.71%), shatter index (98.85%), water resistance (98.35%), and thermal properties, which are the highest volatile matter (94.71%) and the lowest ash content (1.71%). In a nutshell, sugarcane bagasse is a good binder that gives a positive impact to the K.senegalensis pellets in terms of storage and transportation compared to corn cob and rice husk binder.

1. Introduction

It is imperative to make the transition to a mix of renewable energy sources as soon as possible to avoid a true or politically motivated crisis or disruption in the supply of fossil fuels, particularly oil, which could lead to a war [1]. An estimated 37% of the world's total energy is used by the manufacturing sector, primarily in the form of fossil fuels [2]. The use of green energy sources is

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increasingly relevant in combating the consequences of climate change. Biomass is the most common source of renewable energy and has been commonly used in the developing world until recently. Biomass plays a unique role as the primary source of renewable energy for all energy products, agricultural bulk and fine chemicals and hydrocarbon fuels. Therefore, utilising green energy sources is becoming more and more important in the fight against climate change's effects and mitigating fossil fuel depletion. However, biomass is always associated with low bulk density and high moisture content, which hinders its use as fuel. Therefore, densification is needed to curb these issues. Pellet fuel is the best type of renewable energy for reducing various environmental effects while producing energy from biomass [3]. Recently, biomass (biofuel) has been developed as a cost-effective, environmentally benign, renewable, and sustainable fuel [4]. Furthermore, the biomass characteristics are an important criterion for determining the fuel content of a special biomass substance in energetic applications [5]. Therefore, the mechanical and thermal properties of biomass pellets are important to assess, especially for designing and constructing any bioenergy system.

The *Khaya senegalensis* tree grows fast and develops quickly, making it a useful source of pellet fuel. It is a savanna tree with an immediately recognisable round pod and a deciduous round crown of dark, sparkly monocot leaves [6]. Additionally, the species has excellent medicinal potential. The performance of the pellets depends on the type of material used and the process variables used during the pelletization. Densification substantially increases the density of the biomass, thus making unit operations such as handling, storage, and transport cost-effective and economically feasible [2]. The thermal properties of the pellets are essentially dependent on the raw material, and the physical parameters often depend on the pelletizing process.

The utilisation of binders in pellet fuel has been extensively utilised in the pellet manufacturing sector as a means to manufacture pellets of high quality. Binders can exist in either solid or liquid states, serving the purpose of enhancing the adhesion between various components. In addition, the binder also exerted an influence on the pellet's quality. The performance of the pellet was influenced by the composition of the waste material binder, namely the lignin content, which in turn affected the density and calorific value of the pellet [7]. This study examines the impact of utilising waste materials, including rice husk, corn cob and sugarcane bagasse, in the production of pellets on the mechanical and thermal characteristics of fuel pellets.

Although fuel pellets derived from biomass sources show potential as a sustainable energy solution due to their consistent quality and convenient handling, there are still obstacles to overcome in order to maximise their composition for effective energy utilisation. The physical characteristics of raw biomass and waste material binders, commonly employed in the manufacturing of pellets, are subject to certain constraints. The restrictions include low density, variability in composition, and insufficient mechanical qualities collectively impede the widespread application of these materials as a feasible energy source. Previous studies have recognised the existence of these difficulties, however, there is still a significant gap in the literature regarding a thorough examination of the influence of distinct waste material binders on the mechanical and thermal characteristics of *Khaya senegalensis* pellets. The present study highlights the potential of utilising sugarcane bagasse as a binder for *Khaya senegalensis* pellets. Furthermore, it provides insights into the favourable effects of using sugarcane bagasse as a binder on storage and transportation efficiency, in comparison to binders derived from corn cob and rice husk. This work elucidates the distinct benefits of utilising sugarcane bagasse as a binding agent, hence providing valuable insights for the enhancement of biomass pellet characteristics in terms of energy efficiency and ecological sustainability.

2. Methodology

Pellets were produced from *Khaya senegalensis* and plant residues, i.e., rice husk, corn cob, and sugarcane bagasse, using waste materials as binder. The ASTM standard ASTM D3172 was adopted for the proximate analysis, while the ASTM analytical method was used to determine the mechanical properties, as prescribed by Nhuchhen *et al.*, [8].

The attributes of the pellets were assessed according to established standards, which were based on two distinct properties: mechanical characteristics encompassing density, bulk density, durability, moisture content, compressive strength (both axial and diametral), impact resistance, and water resistance. Regarding the thermal properties, the quantification of ash content, volatile matter, fixed carbon, and calorific value were also evaluated.

The experimental procedure was initiated with the equipment setup conducted in Universiti Malaysia Perlis (UniMAP) and the subsequent collection of raw samples, specifically *K. senegalensis*. Rice husk, maize cob and sugarcane bagasse have been selected as pellet binding agents due to their widespread availability in the market at a low cost, making them economically viable options. Prior to use, all materials have undergone a preliminary treatment procedure which encompasses drying, size reduction through grinding, and screening utilising an automated sieve shaker. The materials were thoroughly blended and adjusted to their optimal moisture level before undergoing the pelletization process. Table 1 presents the data pertaining to the proportion, weight, and moisture content of the binder for each sample of *K. senegalensis*.

Table 1
The percentage/weight and moisture content of binder for each *K. senegalensis* sample

Sample	Types of Waste Material Binders	Percentages of Waste Material Binders	Weight of Waste Material Binders (g)	Percentages of *K. Senegalensis (%)*	Weight of *K. Senegalensis* (g)	Moisture Content of *K. Senegalensis* (%)
S1	Rice	10	0.1	90	0.9	10.6
S2	Corn	10	0.1	90	0.9	7.4
S3	Sugarcane Bagasse	10	0.1	90	0.9	10.4

2.1 Bulk Density Test

The determination of bulk density was performed in accordance with the Standard Test Method for Bulk Density of Densified Particulate Biomass Fuels (ASTM E 873-82). The weight of an empty container has been measured and recorded. The next stage is to precisely fill the measuring container (cylinder shape) to the brim with pellets. To account for settling, the container was tapped five times. Then, the pellet-filled container was weighed, and the total weight was recorded.

$$\rho_b = \frac{w_{bs} - w_b}{v_b} \tag{1}$$

In Equation (1), ρ_b is the bulk density (g/cm^3), m is the total mass of pellet (g), v is volume of container (cm^3)

2.2 Durability Test

Each pellet underwent durability testing, was weighed using a weighing scale, and afterwards recorded as the original mass of the pellet. Each pellet sample was subjected to shaking for a duration of 10 minutes using a sieve shaker, at 50 revolutions per minute. The durability test was carried out in accordance with the internationally recognised requirements outlined in DIN EN 15210-1. The pellet durability was computed using the following Equation (2) below.

$$\text{PDI or Durability} = \left[100\% - \left(\frac{\text{Initial weight} - \text{Final weight}}{\text{Initial weight}} \times 100\%\right)\right] \tag{2}$$

2.3 Compressive Strength Test

The mechanical strength of pellets is defined as the force required for sample disruption. For a pellet strength test, a single pellet was positioned between the two flat and parallel plates of a testing machine compression testing device. The top plate compressed the pellet at the speed of 1 mm min-1 and the force increased. Compressive strength was performed according to ASTM D792-13 standard and determined according to Equation (3) below:

$$\sigma = \frac{F}{A} \tag{3}$$

In (3) σ is the compressive strength, F is the force, A is the area of cylinder of pellet.

2.4 Shatter Index Test

This attribute was established in compliance with the guidelines outlined in ASTM D440-86. The sample had to be gravitationally dropped from a fixed height of 2 metres after the original mass of the pellets had been weighed and recorded. The experiment involved conducting three repetitions of the drop, with each repetition involving the passage of the material through a 2 mm sieve. The mass of the pellet retained on the sieve was recorded for each repetition. The shatter index of each pellet was calculated utilising the subsequent Equation (4):

$$K = (B_z / B) \text{ X } 100 \tag{4}$$

In (4), B_Z is the weight after drop and B is the weight before drop.

2.5 Water Resistance Test

Water resistance biomass tests were conducted in compliance with STRI Guide 1, 92/1. The tap water was filled with a spray bottle that could create a fine mist. The sample was sprayed 1-2 times per second from a distance of 25 cm. The hydrophobicity rating shall be determined 10 seconds after the sprinkling is complete. Before and after weighing the pellets, the relative weight changes were recorded. The percentage of water absorbed was calculated using the following Equation (5):

$$\text{WA}(\%) = \frac{W_i - W_0}{W_0} \times 100 \tag{5}$$

In (5), WA is the water absorption, Wi is the total mass after immersion and W0 is the total mass before immersion.

$$\text{Water Resistance } (\%) = 100 - \text{WA } (\%) \tag{6}$$

2.6 Moisture Content Test

The pellets were inserted into the digital moisture analyzer, and the resulting data has been recorded. The utilisation of the digital moisture analyzer is preferred for this procedure due to its enhanced precision and expedited processing capabilities. The moisture content test was conducted in accordance with the ASTM E 871-82 standard.

2.7 Ash Content Test

Ash content was measured through the assessment of the residual mass following heating of the air-exposed sample. The sample had been positioned within the furnace and subjected to heating for approximately 4 hours at around 500°C. The percentage of ash content within the biomass pellets was ascertained utilizing the standard Equation (7).

$$\text{Ash content } (\%) = \frac{\text{Final weight}}{\text{Initial weight}} \times 100\% \tag{7}$$

2.8 Volatile Matter Test

Volatile matter was carried out under ASTM E 872-82 standard. The volatile matter test begins by seven minutes setting the sample inside a furnace at 950 ° C. The percentage of volatile matter in the biomass pellets was determined using the following standard Equation (8):

$$\text{Volatile Matter } (\%) = \frac{\text{Final weight}}{\text{Initial weight}} \times 100\% \tag{8}$$

2.9 Fixed Carbon Test

The pellet's fixed carbon content can be connected to the anticipated pellet production. It is the carbon present in the residual material after removal of volatile materials. The value can be derived from the following Equation (9):

$$\text{Fixed Carbon} = 100(\%) - \text{VM}(\%) + \text{AC}(\%) \tag{9}$$

2.10 Calorific Value Test

Calorific value test calculates the total heat produced by the pellets when the combustion is completed. The standard biomass calorific value is about 14 MJ/kg - 18 MJ/ kg. The calorific value of the pellet shall be determined by using the following Equation (10):

$$\text{HHV} = 19.2880 - 0.2135 \times \frac{\text{VM}}{\text{FC}} + 0.0234 \times \frac{\text{FC}}{\text{AC}} - 1.9584 \times \frac{\text{AC}}{\text{VM}} \tag{10}$$

3. Results

The effects on pellets are different for all three different types of binders, such as rice husk, corn cob, and sugarcane bagasse. Thermal and mechanical properties, including ash content, volatile matter, and moisture content, are discussed.

3.1 Unit Density

Figure 1 shows that when *K. senegalensis* pellets bind with sugarcane bagasse, they produce a higher mean value in unit density than other waste material binders. This is due to the higher cellulose content of sugarcane bagasse, which lowers the operating pressure for densification [9]. Besides, pellet density can be influenced by the lignin content of lignocellulose biomass, which differs inter-species. According to the previous study by Thiffault *et al.*, [10], the pellets with the highest lignin content have the highest density.

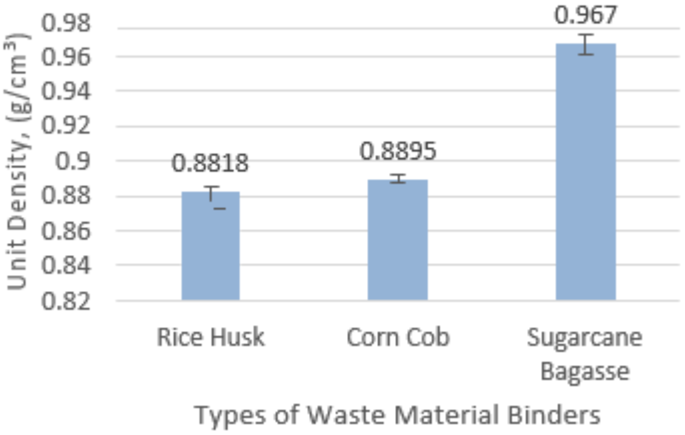

Fig. 1. The effect of the different kinds of binding agent to *Khaya senegalensis* pellet unit density

3.2 Bulk Density

Based on Figure 2, which can be seen in the graph below, sugarcane bagasse resulted in the highest bulk density amongst the three types of binding agents. This indicates that sugarcane has a good impact on bulk density and transportation. The shape and size of pellets are influenced by the cellulose content of the biomass, and the cellulose affects pelletization behaviour [9]. In addition, bulk density was also affected due to the elongation of the pellets. This is because the pellets expanded and increased in volume when exposed to an open environment, which can absorb moisture [11].

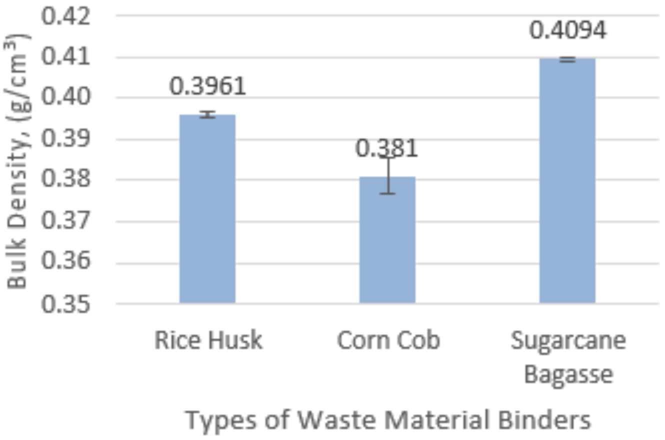

Fig. 2. The effect of the different kinds of binding agents on *Khaya senegalensis* pellet bulk density

3.3 Moisture Content

According to Figure 3, the highest-ranking pellets were made from sugarcane bagasse and rice husks, which will not have developed fungal growth as they did not absorb moisture. Prior to processing, the raw biomass had a moisture level of 10.6%; the moisture content of the pellet was 9.76%. This is brought on by changes in temperature while the pellets are kept [12]. Despite having the lowest moisture level of all the pellets, corn cobs will yield a high calorific value [13].

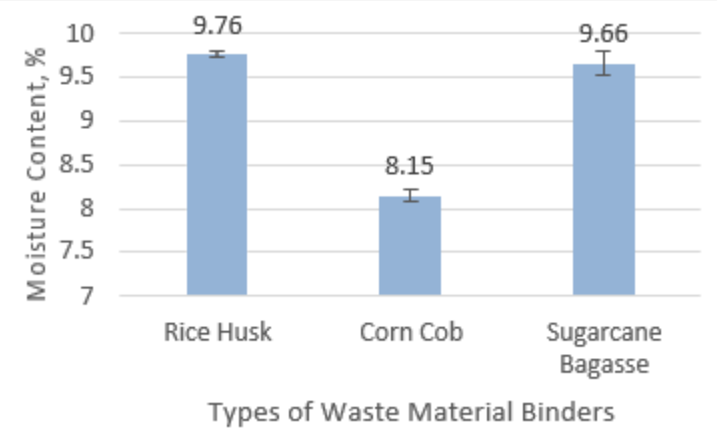

Fig. 3. The effect of various binding agents on the *Khaya Senegalensis* pellet moisture content

3.4 Durability

As can be seen in Figure 4, sugarcane bagasse pellets are the most durable, in contrast to rice husks and corn cob pellets. The pellet has the smallest diameter, making it more durable and less prone to breakage. The lignin content of biomass may also influence the durability of pellets [14]. The greater the lignin content of the raw materials used for pellet production, the greater the durability value.

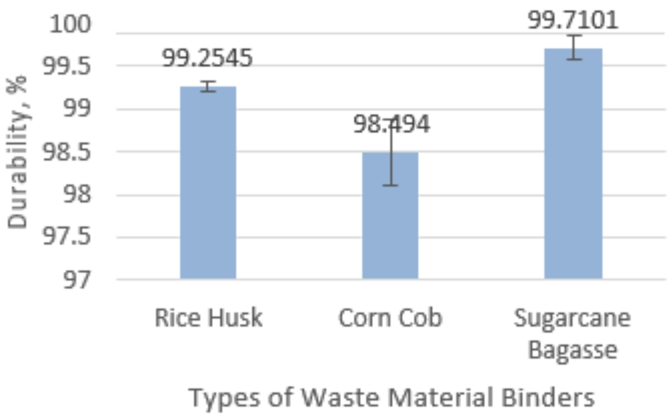

Fig. 4. The effect of various binding agents on the *Khaya Senegalensis* pellet durability

3.5 Axial and Diametral Compressive Strength

As depicted in Figures 5 and 6, the compressive strength of the rice husk pellet exhibits the maximum value, while the corn cob pellet demonstrates the lowest compressive strength value. According to a study by Liang *et al.*, [15] rice husk pellets have superior compressive strength due to the presence of cellulose inside the biomass. The pellets' capacity to endure compression force increases in direct proportion to the cellulose concentration. The compressive strength of the pellets was controlled by the quantity of cellulose component. The enhanced mechanical strength of organic pellets was mostly attributed to the cohesive forces exhibited by the pellets. Polysaccharide binders are commonly referred to as "glue" during the compression process due to their notable flowability and sticky characteristics. Under the influence of external forces, carboxymethyl cellulose in biomass material migrated or dispersed via interstitial spaces between adjacent particles, ultimately reaching the internal porous surface of hydrocarbon particles. This process resulted in the formation of robust bridges, effectively establishing strong interconnections among the hydrocarbon particles.

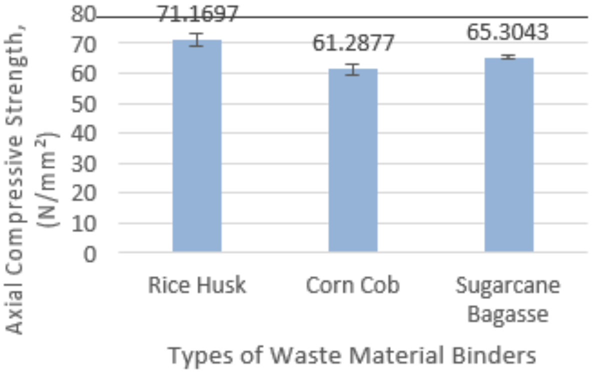

Fig. 5. The effect of various binding agents on the *Khaya Senegalensis* Axial Compressive Strength

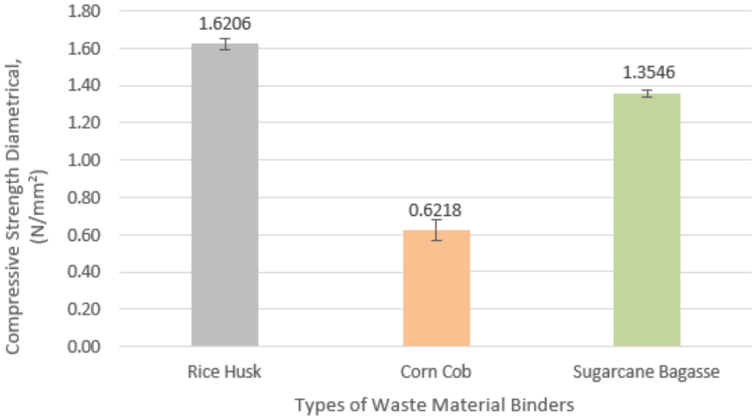

Fig. 6. The effect of various binding agents on the *Khaya Senegalensis* Diametral Compressive Strength

3.6 Shatter Index

According to the data presented in Figure 7, it can be observed that the sugarcane bagasse pellet exhibits the highest shatter index, while the pellet corn cob binder demonstrates the lowest shatter index. The quantification of lignin content inside the biomass serves as a critical determinant in assessing the pellet's ability to endure impact. Sugarcane bagasse pellets exhibit a superior shatter index owing to their elevated lignin composition. The presence of lignin in the biomass facilitates the cohesive bonding of particles, akin to the adhesive properties of glue [16]. The thermosetting characteristics of lignin-rich biomass led it to undergo softening when subjected to high pressure during compression. The lignin that has been softened serves as an adhesive substance. This is the reason why, in comparison to corn cob pellets, sugarcane bagasse pellets exhibit greater resistance to drop impact and do not experience any breakage. According to the cited source, Borowski *et al.*, [17] it is recommended that the shatter index of briquettes should be no less than 90%.

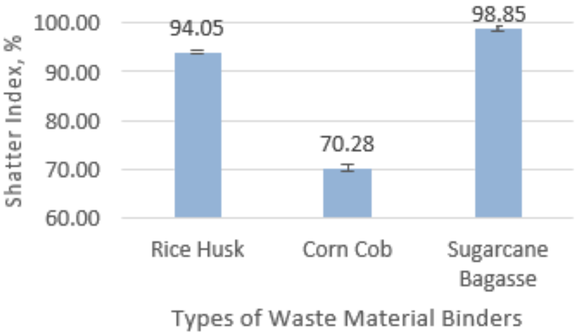

Fig. 7. The effect of various binding agents on the *Khaya Senegalensis* pellet shatter index

3.7 Water Resistance

Sugarcane bagasse as a binder has the highest water resistance in Figure 8 due to its high pellet density and low porosity [18]. The observed superior water resistance of fuel pellets utilizing sugarcane bagasse as a binder can be attributed to specific material properties inherent to sugarcane bagasse and the resultant pellet characteristics. The interaction of these factors plays a pivotal role in influencing water resistance. Sugarcane bagasse, a residue from sugar production, possesses intrinsic qualities that contribute to enhanced water resistance. The high pellet density associated with sugarcane bagasse as a binder creates a more compact and tightly packed structure. This characteristic minimizes the presence of open spaces or pores within the pellets, thereby reducing avenues for water infiltration. This low porosity impedes the absorption of water, rendering the pellets less susceptible to moisture-induced degradation.

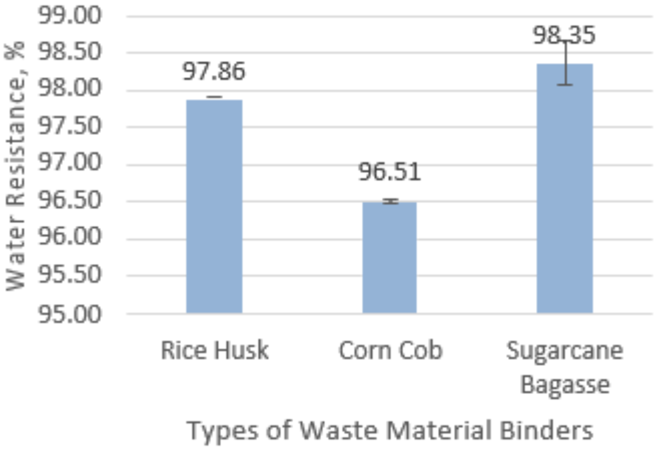

Fig. 8. The effect of various binding agents on the *Khaya Senegalensis* pellet water resistance

A high hemicellulose content influences water uptake [19]. Fuel pellets must show a high resistance to water uptake, particularly if the feedstock is farm residue. Also, according to Kpalo *et al.*, [18] an elongation of more than 70% was considered acceptable, and more than 80% was suggested to be most ideal for fuel pellet shape. Moreover, the high hemicellulose content in sugarcane bagasse can also influence water uptake. Hemicellulose is a polysaccharide component of cell walls that can absorb and hold water due to its hydrophilic nature. Higher hemicellulose content in the pellets can potentially lead to greater water absorption. However, the concurrent influence of pellet density and porosity, along with hemicellulose content, collectively dictates the overall water resistance.

A prior work by Zhang *et al.*, [20] also did a similar analysis, focusing on the synthesis and characterization of hybrid briquettes made from corncobs and oil palm trunk bark using a low-pressure densification approach. The findings indicated that the hybrid briquettes exhibited water resistance levels ranging from 87.60% to 92.00% in terms of their physical qualities.

3.8 Ash Content

The ash content describes the amount of incombustible material that remains after a sample of the furnace's biomass has been entirely burned. The ash content of the fuel pellet is normally low. It is referred to as inorganic residue because it remains in the air at specific high temperatures after biomass burning. Figure 9 demonstrates that the highest ash level is found in rice husk binder pellets, whereas the lowest is found in sugarcane bagasse pellets. High-ash biomass fuels are prone to sludge and blockage [21]. Previous research by Zuo *et al.*, [22] has demonstrated that low-ash biomass has a higher combustion efficiency. High ash concentrations cause additional problems, such as damage to equipment structures. It not only limits handling and burning capacities, but it also increases handling costs and influences combustion efficiency. Because of the low average ash content and high capacity for biomass self-consumption, the conditions were suitable for the development of a pellet mill.

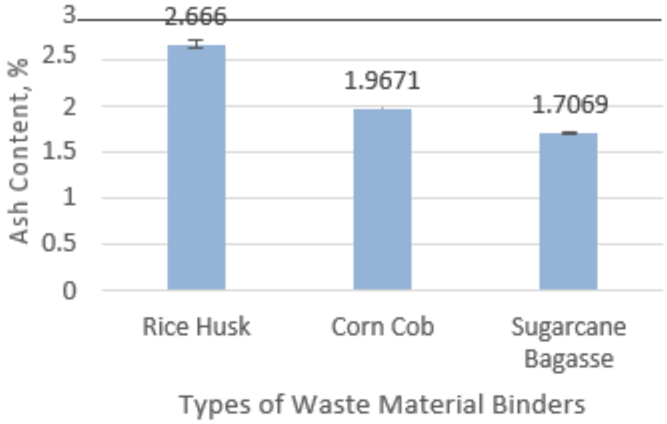

Fig. 9. The effect of various binding agents on the *Khaya Senegalensis* pellet ash content

3.9 Volatile matter

Figure 10 below shows the sugarcane bagasse has the highest volatile matter and is therefore easier to ignite, has great flammability, and has improved carbon burnout. Corn cob pellets have some non-combustible elements, which means that the volatile material value of the corn cob is lower than that of the other pellets. Biomass is considered an acceptable fuel for thermal conversion if volatile matters are high [23]. Fuel pellets with a high volatile matter content would be easy to ignite during combustion.

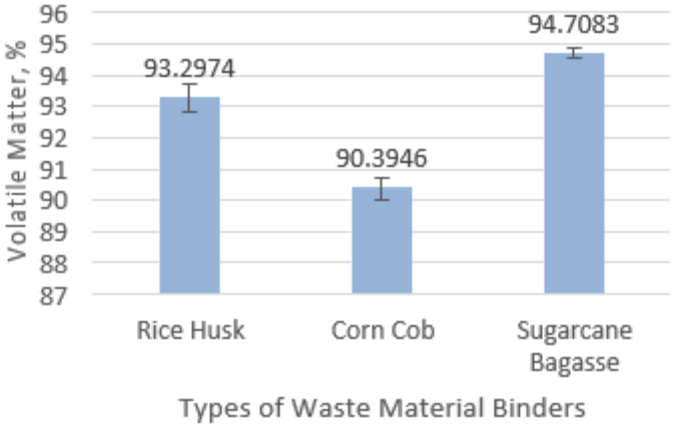

Fig. 10. The effect of various binding agents on the *Khaya Senegalensis* pellet volatile matter

3.10 Fixed Carbon

Corn cob pellet has the highest fixed carbon value, as shown in Figure 11, and sugarcane bagasse pellet has the lowest fixed carbon value. This indicates that the pellet will require a long combustion time [24]. Corn cob pellets would be more sustainable for power generation. The amount of fixed carbon contained in corn cob pellets is higher than that contained in the other raw residues, which of course have a large influence on the calorific values. This means that the flame of the corn pellet would last for a long time, even though it takes time to burn and provides a high calorific value [25].

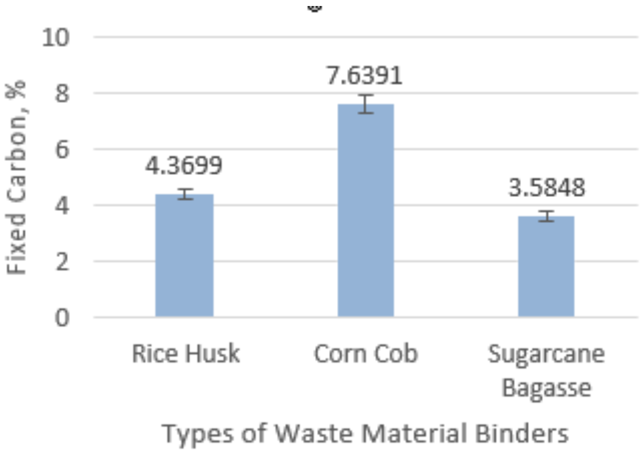

Fig. 11. The effect of various binding agents on the *Khaya Senegalensis* pellet fixed carbon

3.11 Calorific Value

Because of the moisture level in the biomass, *K. senegalensis* pellets bound with corn cob produced the maximum calorific value compared to sugarcane bagasse pellets (Figure 12). The calorific value of biomass was lower in samples with higher moisture content than in samples with lower moisture levels. It has been discovered that the heat value of solid biofuels increases as moisture decreases [26]. The less energy required in the combustion process to evaporate water, the drier the biofuel. The lower the moisture content, the higher the net heating value of the combustion pellet. Therefore, the less energy is required in the combustion process to evaporate water, the more productive the biofuel.

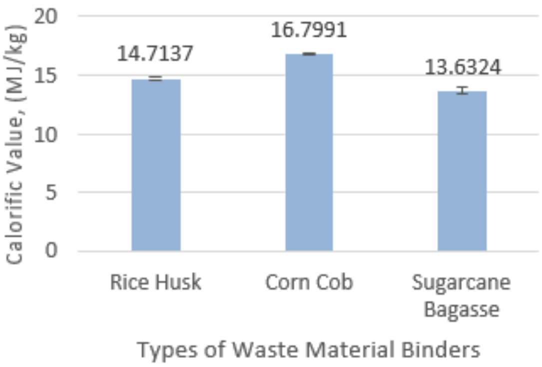

Fig. 12. The effect of various binding agents on the *Khaya Senegalensis* pellet calorific value

4. Conclusions

The objective of this research was to determine the effect of different types of waste material binder on *Khaya senegalensis*' pellet properties. Sugarcane bagasse pellets had the highest unit density, bulk density durability, shatter index, and water resistance values of any material tested. The rice husk pellet had the highest compressive strength value. Corn cob pellets had the highest calorific value due to their high lignin content and optimal moisture content, which improved combustion performance. It was found that the highest volatile matter and the lowest ash content were offered by sugarcane bagasse, while corn cobs have the highest fixed carbon. The research found that sugarcane pellets are preferred as a binding agent that will produce high-quality *Khaya senegalensis* energy pellets.

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