Mechanical and Physical Properties of *Khaya senegalensis* Solid Fuel Pellet with Different Binder Percentages

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Abstract. The characteristics of the solid fuel pellets, such as its strength, durability and density can be used to assess its quality. During the transport and storage, pellets with low strength and durability produces dusts and ultimately resulting in equipment blockage, high pollution emissions, and an increased risk of fire and explosion. Therefore, pellet manufacturing process should be given priority to improve pellet quality. The use of binder in the production of pellets will aid in improving pellet quality. Therefore, this study investigates the influence of different binder percentages on the mechanical properties of *K. senegelensis* fuel pellets. Durability, unit density, bulk density and diametral compressive strength testing were carried out in compliance with international standards. It was discovered that pellets containing 4% cassava starch binder produces better results, particularly in terms of durability and compressive idiametral strength.

1. Introduction
In Europe, biomass pellets are one of the most widely used major fuels. These pellets are often utilised as a source of energy, culinary fuel, commercial heating fuel, and housing fuel. There will be various steps in the pellet production, including processing, packaging, transportation, and storage. Pellets are easy to employ due to their easy-to-handle shape. The physical and mechanical quality of solid biofuels, especially pellets are characterized by the durability and density of particle pellets [1]. During the transport, handling and storage of energy pellets, pellets with low resistance could cause various problems such as system blockage and trigger higher danger like fire and explosion [2]. Binder addition can help strengthen fuel pellets, particularly in terms of resisting compressive strength during transportation and storage. The optimal binder content will have a favourable impact since it will provide great durability and will reinforce the pellet structure. Pellet manufacturing expenses can be reduced and the risk of pellet damaging will be reduced too by selecting the appropriate binder percentage. As a result, choosing the proper amount of binder in the manufacturing of pellets is critical.

Asymmetric forms, low bulk density, high humidity, poor combustion efficiency, and high transport and storage costs are common characteristics of biomass raw materials [3]. Therefore, densification is
important to improve these characteristics in order to make it more viable for long-haul shipping and to improve solid fuel processing and storage. Furthermore, the quality of pellets are determined by the properties of the feedstock form, moisture content, particle size, and addition of binding agent [4], [5]. Pelletized biomass products are viewed as a significant energy source that can replace the use of fossil fuels for a variety of reasons, including the reduction of greenhouse gases such as sulphur dioxide (SO2), nitrogen dioxide (NO2), carbon dioxide (CO2), nitrous oxide (N2O), and methane (CH4) in the atmosphere such as carbon dioxide (CO2), nitrogen dioxide (NO2) and nitrous oxide (N2O) [6], [7].

There are other resources available to all industries that try to reduce environmental pollution, such as solar, wind and etc. In addition to that, biomass pellets can be used as a fuel alternative to non-renewable materials in both private and industrial settings. Pellets are also less expensive than coal, and they may be able to compete with it. Because the European market is so large, these pellets have export potential. Pellets are usually examined after manufacture to determine their quality. There was a promising effect on the durability of all pellets when biomass was mixed with binders, according to a study [8]. The use of binders has shown to enhance the strength of pellets formed from biomass exhibiting lower binding abilities. Besides, in another study, it was investigated that pellets without binding agents have a compressive strength of 64 N/cm, and when pellets with 1% binder weight gave the maximum compressive strength of 107 N/cm. Nevertheless, when binder percentage improved to 2% and 3%, strength decreased to 70 N/cm and 63 N/cm respectively [9]. Apart for that, mechanical compression measurements are also used to assess the pellets’ mechanical strength at lower pressure speeds and tested using universal testing machine [2].

2. Methodology
The study explored the use of binder in the production of K. senegalensis solid fuel pellets at various percentages. The mechanical and physical properties of the pellet, such as compressive strength, unit density, bulk density, and durability are examined in this study. The experiment started with the procurement of the raw samples from K. senegalensis trees as well as planning and preparation for the Universiti Malaysia Perlis (UniMAP) equipment. Additionally, the khaya branches were being pretreated, which involve wood chipping, grinding, and sieving. Cassava starch was chosen as the binding agent for pellets because it is easily obtainable at an affordable price. Most notably, the binding characteristics of cassava starch can enhance the pellet structure.

2.1. Pelletization
The process started harvesting raw materials (K. senegalensis) and followed by cutting, grinding and reducing particle size. The ground raw material was then placed in a sieve shaker until the required 0.5 mm particle size is attained for use during the pelleting process. The binder particle size was also 0.5 mm. The binder and khaya ground raw material were then mixed and weighed for 1 g before being put into a 10 mm diameter mould. Table 2.1 provides the proportion of binder and raw material weight K. senegalensis for each binder percentage. The work is then placed inside the single press machine and compressed at 3 tonnes (18.8MPa). The pellet were taken out from the mould carefully after the densification process and subjected to various mechanical testing afterwards.

| Percentages of cassava starch (%) | Weight of cassava starch (g) | Percentages of K. senegalensis (%) | Weight of K. senegalensis (g) |
|----------------------------------|------------------------------|-----------------------------------|------------------------------|
| 0                                | 0                            | 100                               | 1                            |
| 4                                | 0.04                         | 96                                | 0.96                         |
| 8                                | 0.08                         | 92                                | 0.92                         |
| 12                               | 0.12                         | 88                                | 0.88                         |
| 16                               | 0.16                         | 84                                | 0.84                         |

2.2. Pellet Properties Testing
Mechanical and physical characteristics tests were conducted to measure the durability, unit density, bulk density and diametral compressive strength of pellets. These tests were reproduced three times.
The precision of the measurement data sets are determined by calculating the average deviation of the measurement. First, the average value of all measurements are calculated. Then the deviation of each measurement is determined and later all the deviations are added up and divide by the number of measurements of obtain average deviation. The uncertainty can then be expressed as a percentage by dividing the average variation by the average measurement value and multiplying the result by 100.

2.2.1. Density Calculation. Density refers to the mass of pellets in relation to their volume. Pellet mass data were weighed and recorded. Then, using a vernier calliper with a resolution of 0.05 mm, the volume of the pellet was determined by measuring its diameter and height allowing a measurement of ± 0.005 cm. Density test conducted in accordance with the ASTM D792-13 standard. Following the particle density test, the pellet density was determined using Equation 1 below.

\[ \rho = \frac{m}{v} \]  

Where \( \rho \) is the density (g/ cm\(^3\)), \( m \) is the mass (g), \( v \) is volume (cm\(^3\)).

2.2.2. Bulk Density Calculation. The bulk density is dependent on the particle density and volume. The bulk density was determined using the mass of the substance divided by the volume of the container. The container used was a beaker with a capacity of 50 ml ± 1 ml uncertainty. The pellets were filled to the container's top surface and weighed using a Sartorius BSA 224S-CW digital scale of 0.1 mg accuracy. The capacity of the container was determined by the diameter and length of the container. The bulk density of \( K. \) senegalensis pellets (\( \rho_b \)) was determined according to the ASTM 873-82 Standard method, using Equation 2 follows.

\[ \rho_b = \frac{m_b}{v_b} \]  

Where \( \rho_b \) is the bulk density (g/ cm\(^3\)), \( m_b \) is the total mass of pellet (g), \( v_b \) is volume (cm\(^3\)).

2.2.3. Durability Calculation. This test was used to determine the durability of \( K. \) senegalensis pellets by examining the strength and structure of pellets generated using the pellet durability index (PDI) or percentages of durability. This investigation began with the weighing of a pellet sample to get the beginning weight. The pellets were then shaken for 10-15 minutes at 50 rpm in a sieve shaker. Following completion, the pellet sample was further weighed to establish the pellet's final weight. Finally, the PDI, or durability, was determined by dividing the weight after filtering by the weight before to sifting and multiplying by 100. International standard CEN/TC 335 was used to conduct this durability test. EN 15210 - 1: 2009. The durability of pellets was evaluated using Equation 3 beneath.

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

2.2.4. Compressive Strength. Strength has been used to determine the quality of pellets by subjecting them to a compressive strength test against pellets. Diametral compression test can be used to assess the compressive strength of the pellet. Pellet strength was determined at a compression speed of 1 mm/min on a Shimadzu Autograph AGS-X series 250 kN universal testing machine. This UTM machine has a test speed accuracy of ±0.1%. The load is increased at a constant rate until the test specimen fractures or breaks. The diametral compressive strength was determined using Equation 4 in accordance with ASTM D2166-85.

\[ \sigma = \frac{2P}{\pi LD} \]  

Where \( \sigma \) is the diametral compressive strength, \( P \) is the force, \( L \) is the length and \( D \) is the diameter.
3. Results And Discussion

3.1. Unit Density
Figure 3.1 shows the unit density of *K. senegalensis* biofuel pellets with different percentage of binder. The precision of this set of measurements is 1.027%. It can be seen that a binder percentage of 16% produced the highest unit density mean value whereas khaya pellets made with 0% cassava starch resulted in the lowest unit density value. Binder bridges the gap between raw materials that makes strong bonding of biomass components. Without a binder, the pores in the material remain unfilled, resulting in a pellet that is not dense or compressed. According to some national regulations, the density of pellet particles serves as a benchmark for the quality of densified fuel [10]. This is corroborated by [11], which stated that biomass pellet density could be increased by 20% by adding binders. Therefore, binders can be added to the feed to improve pellet quality standards or market requirements [12].

**Figure 3.1:** Unit density of *K. senegalensis* biofuel pellets with different percentage of binder.

3.2. Bulk Density
As illustrated in Figure 3.2, the bulk density of *K. senegalensis* biofuel pellet quality with different percentage of binder ±0.117% uncertainty. The highest mean value was noticed for the 12% binder percentage while the lowest mean value was recorded for samples with 4% binder percentage. This is because increasing the quantity of natural additives or binders increases bulk density. The mixture comprised of a high concentration of binders resulted in a more compacted pellet than others. Binder filled the tiny spaces between the pores of the pellet. As a result, the pellets produced with higher binder percentages were having lower volumes and thus denser than other pellets. This data was likewise observed in the study conducted by [13] with additions of 5% wood bark binders to wood pellets resulting in an increase in bulk density to 22 kg/m$^3$. On top of that, [14] also noted that adding binders significantly increased the density of wheat straw pellets. The bulk density is normally under 100 kg/m$^3$ (or agricultural residues [15]. The bulk density of khaya pellets shows a promising improvement with densification and binder addition, ranging from 433.5 to 492.9 kg/m$^3$.

**Figure 3.2:** Bulk density of *K. senegalensis* biofuel pellet quality with different percentage of binder.

3.3. Durability
The durability of the pellet is affected by the five different binder percentages as shown in Figure 3.3. The 4% binder has the highest durability of 99.2598% followed by 99.2003% for the 0%, 98.9862% for the 8%, 98.6959 for the 12%, and 16% = 97.7677% with a ±0.077% uncertainty. Pellet durability is lowest in the sample having the highest amount of binder. This is because the composition with too high amount of binding agents produces weaker bonding between the particles and they easily fracture when...
mechanical forces are applied. In the pellet industry, the durability of the pellet is very important, whether for storage, transportation, or handling, so that the pellet can withstand the occurrence of cracks or worse, the occurrence of destruction or breakage during the process. This is supported by a research in which [16] added cassava starch to the biomass mixture in the pellet manufacturing process to improve the durability of the fuel. In general, the higher the durability of the pellet, the stronger the pellet. Mechanical durability should generally be greater than 96.5% and pellets with a durability of more than 97.5% are considered high-quality biofuel.

![Durability of K. senegalensis biofuel pellet quality with different percentage of binder.](image1)

### 3.4. Diametral Compressive Strength
A difference in the khaya pellets compressive strength diametric with different binder percentage may be indicated based on Figure 3.4. The diametric compressive strength here is reported with a ±0.701% uncertainty. It was discovered that pellets with 4% binder shows the greatest compressive strength, while with 16% cassava starch, the samples were found to have the lowest compressive strength. Binder percentages greater than 8% demonstrate a decreasing trend. The average compressive strength of the pellet declined from 2.2315 MPa to 1.2352 MPa, is most likely due to the lower amount of wood biomass and higher amount of binder. This resulted in pellets being dry and brittle due to an excessive amount of binder ingredient. This affects the bonding and transformation processes within the biomass mixture throughout the densification process. The pellets’ bonding forces are primarily attraction and cohesion forces, which include hydrogen bonds, Van Der Waals forces, and mechanical interlock. However, the compressive strength of the pellets is, on the contrary, enhanced by the addition of starch, as noted by [17]. This could be explained by the fact that various species have varying compressive strengths.

![K. senegalensis biofuel pellet diametral compressive strength with different percentage of binder.](image2)

### 4. Conclusion
Each distinct binder percentage resulted in distinct qualities, i.e mechanical and physical properties for the *K. senegalensis* pellet, including compressive strength, unit density, bulk density and durability. Additions of 4% cassava starch seem to have the best result. Further studies would be required to assess the overall life-cycle energy requirement of the pelletization process. Overall, biomass pellets from *K. senegalensis* offer an intriguing alternative fuel source.

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References

[1] A. Garcia-Maraver, M. L. Rodriguez, F. Serrano-Bernardo, L. F. Diaz, and M. Zamorano, “Factors affecting the quality of pellets made from residual biomass of olive trees,” Fuel Process. Technol., vol. 129, pp. 1–7, 2015.

[2] O. Williams, S. Taylor, E. Lester, S. Kingman, D. Giddings, and C. Eastwick, “Applicability of mechanical tests for biomass pellet characterisation for bioenergy applications,” Materials (Basel.), vol. 11, no. 8, 2018.

[3] W. Intagun, W. Kanoksilapatham, A. Maden, and B. Nobaew, “Effect of natural additive on pellets physical properties and energy cost,” 2019 IEEE 2nd Int. Conf. Renew. Energy Power Eng., pp. 130–134, 2020.

[4] R. Garcia, M. V. Gil, F. Rubiera, and C. Pevida, “Pelletization of wood and alternative residual biomass blends for producing industrial quality pellets,” Fuel, vol. 251, no. January, pp. 739–753, 2019.

[5] P. Gilbert, C. Ryu, V. Sharifi, and J. Swithinbank, “Effect of process parameters on pelletisation of herbaceous crops,” Fuel, vol. 88, no. 8, pp. 1491–1497, 2009.

[6] J. M. C. Ribeiro, R. Godina, J. C. de O. Matias, and L. J. R. Nunes, “Future perspectives of biomass torrefaction: Review of the current state-of-the-art and research development,” Sustain., vol. 10, no. 7, pp. 1–17, 2018.

[7] E. Oveisi-Fordiee, “Durability of wood pellets,” 2011.

[8] S. P. Rajput, S. V Jadhav, and B. N. Thorat, “Methods to improve properties of fuel pellets obtained from different biomass sources: Effect of biomass blends and binders,” vol. 199, no. October 2019, 2020.

[9] Lakshika Hettiarachchi, Nilanthi Jayathilake, Sudarshana Fernando, and S. Gunawardena, “Effects of compost particle size, moisture content and binding agents on co-compost pellet properties,” Int. J. Agric. Biol. Eng., vol. 12, no. 4, pp. 184–191, 2019.

[10] Z. Liu, X. Liu, B. Fei, Z. Jiang, Z. Cai, and Y. Yu, “The properties of pellets from mixing bamboo and rice straw,” Renew. Energy, vol. 55, pp. 1–5, 2013.

[11] M. Stahl, J. B. Karlstads, K. Granstr, and R. Renstr, “Effects on Pellet Properties and Energy Use When,” Energy & Fuels, vol. 26, no. November 2015, pp. 1937–1945, 2012.

[12] P. Pradhan, S. M. Mahajani, and A. Arora, “Production and utilization of fuel pellets from biomass: A review,” Fuel Process. Technol., vol. 181, no. October, pp. 215–232, 2018.

[13] M. Younis, S. Y. Alnouri, B. J. A. Tarboush, and N. Mohammad, “Renewable biofuel production from biomass: a review for biomass pelletization, characterization, and thermal conversion techniques,” Int. J. Green Energy, vol. 00, no. 00, pp. 1–27, 2018.

[14] D. Lu, L. G. Tabil, D. Wang, G. Wang, and S. Emami, “Experimental trials to make wheat straw pellets with wood residue and binders,” Biomass and Bioenergy, vol. 69, no. 17, pp. 287–296, 2014.

[15] S. Larsson, Fuel Pellet Production from Reed Canary Grass Supply Potentials and Process Technology. 2008.

[16] O. Lockneus, S. Larsson, and R. Samuelsson, “Cassava as an additive in biomass fuel pellet production,” 2014.

[17] L. Jezerska, O. Zajonec, J. Rozbroj, J. Vyletělek, and J. Zegzulka, “Research on Effect of Spruce Sawdust with Added Starch on Flowability and Pelletization of the Material,” IERI Procedia, vol. 8, pp. 154–163, 2014.