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Thermal Characteristics of Malaysian *Khaya Senegalensis* Wood Fuel Pellets: Densification-Induced Changes at Different Feedstock Moisture Levels

Ras Izzati Ismail[1,*], Chu Yee Khor[1], Alina Rahayu Mohamed[2]

[1] Faculty of Mechanical Engineering & Technology, Universiti Malaysia Perlis (UniMAP), 02600 Arau, Perlis, Malaysia
[2] Faculty of Chemical Engineering & Technology, Universiti Malaysia Perlis (UniMAP), 02600 Arau, Perlis, Malaysia

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ABSTRACT

This study investigates the thermal behaviour of Malaysian *Khaya senegalensis* wood energy pellets, examining the effects of densification at different feedstock moisture levels. Densified wood pellets are promising renewable energy sources, but the impact of densification on thermal characteristics, considering various moisture contents, is underexplored. The main objective is to quantify the thermal characteristics, which involved proximate analysis such as energy pellets' ash content, fixed carbon, volatile matter, and calorific value. In this research, Malaysian *Khaya senegalensis* wood was converted into pellets through a densification process, spanning from of 4-20% feedstock moisture levels. The manufactured pellets were then subjected to various tests to characterize the thermal properties. Results reveal compelling insights on the relationships between densification, moisture content, and thermal properties. Densification significantly influenced thermal attributes, with effects tied to initial moisture content. Varying moisture levels led to distinct thermal responses, reflecting interactions between densification-induced changes in moisture and thermal responses. In this study, the best moisture content for ash content was found to be 16%, with 3.24% ash content, 16% moisture content with volatile matter of 85.24%, fixed carbon of 12% from 20% moisture content, and 16% moisture content with calorific value of 19.65 MJ/kg. These findings aid *Khaya senegalensis* wood pellet densification optimization for improved thermal performance. Understanding densification's impact on thermal behaviour under varying moisture conditions enhances pellet efficiency as sustainable energy sources. This research contributes to biomass pellet knowledge for renewable energy applications, advancing efficient and eco-friendly energy solutions.

1. Introduction

The rise in population and the expansion of the economy are driving the need for energy. Hence, it is imperative for developing nations to undertake a shift towards sustainable energy sources in order to ensure the stability of their energy supply and diversify their energy portfolio. Malaysia

[*] *Corresponding author.*
E-mail address: rasizzati@unimap.edu.my

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exhibits untapped potential in the field of biomass that has yet to be fully exploited. This phenomenon can be attributed to the ongoing reliance of the nation on coal and petroleum as primary sources for the generation and use of electricity [1]. The pursuit of sustainable and renewable energy sources has led to considerable interest in biomass-based fuels as a viable and eco-friendly substitute for traditional fossil fuels. Wood pellets have emerged as a viable option among the available choices. They possess several advantages, including lower greenhouse gas emissions, renewable sourcing, and efficient combustion qualities. The development and optimisation of wood pellet production technologies are becoming more crucial as worldwide efforts to slow climate change increase [2].

The process of making wood pellets involves a complex interaction of variables that affect the qualities of the finished product, such as the choice of feedstock, moisture level, and densification techniques. Densification, which refers to the compaction of loose biomass materials into denser and more uniform pellets, has been widely acknowledged as a crucial procedure for improving the energy density and handling properties of these pellets. Nevertheless, the impact of densification on the thermal characteristics of wood pellets, particularly in relation to fluctuations in the moisture content of the raw materials, continues to be an area of active research.

Khaya senegalensis, a tree species frequently encountered along roadways, was deliberately chosen for adoption due to its widespread presence and abundance. Its natural propensity for vigorous growth makes it a valuable resource. However, the rapid rate of growth also necessitates frequent and consistent pruning to maintain its desired shape and size. This need for ongoing pruning opens up a unique opportunity and challenge in resource management. The surplus plant material generated through this process can potentially be harnessed for various beneficial applications, ranging from biomass energy production to the development of sustainable materials. Thus, the conundrum of Khaya senegalensis' rapid growth and pruning requirements presents a promising avenue for leveraging this abundance and addressing both environmental and resource utilization concerns.

In recent times, there has been a growing interest in utilising Malaysian *Khaya senegalensis* wood as a viable source for biomass pellets. This interest stems from its abundant availability and advantageous characteristics, such as its appropriate energy content and minimal ash content. It is imperative to have a comprehensive understanding of the thermal properties exhibited by *Khaya senegalensis* wood pellets and the impact of densification on these attributes. This knowledge is essential for the purpose of maximising their efficacy and sustainability as a viable energy source.

The primary objective of this work is to fill the existing knowledge gap regarding the influence of densification-induced alterations on the thermal characteristics of Malaysian *Khaya senegalensis* wood pellets under varying degrees of feedstock moisture. Through the proximate analysis, changes in volatile matters, fixed carbon, ash content and calorific value that occur as a result of the densification process, this study aims to offer valuable insights into the complex correlation between feedstock moisture, densification, and the thermal properties of biomass pellets.

The results of this work have significance not only for the fundamental comprehension of the thermal behaviour of densified wood pellets but also for real-world applications in the generation of renewable energy. The enhancement of pellet performance, improvement in combustion efficiency, and reduction in environmental impact can be achieved by optimising the densification process and adjusting the moisture content of the feedstock. A thorough understanding of the thermal behaviour of biomass pellets is crucial for influencing the development of renewable energy technologies as the world's energy landscape shifts in favour of greater sustainability [3].

In summary, this study aims to comprehensively investigate the thermal properties of *Khaya senegalensis* wood fuel pellets in Malaysia. The research is motivated by the need to understand the intricate interactions governing these properties, particularly in the context of various densification at different feedstock moisture levels. In the forthcoming sections, the methodology, experimental design, and key findings of the study will be explored. Through rigorous examination, valuable insights into the thermal behaviour of *Khaya senegalensis* wood fuel pellets will be provided, contributing to the knowledge base in this field.

2. Methodology

In this experiment, the shredded khaya wood was ground using an IKA microfine grinder mill to produce a powder form of the khaya tree branch. Next, the raw khaya wood feedstock was divided into different moisture content levels. This experiment was designed one factor at a time, replicated three times, with five levels of moisture content (4%, 8%, 12%, 16%, and 20%) determined by using moisture analyser according to ASTM-E 71. The ground biomass feedstock was pelletized using a Specac hydraulic single pellet press. A total mass of 1.0 g ± 0.005 of material was put into the 10 mm diameter. After a uniform pump was exerted on the mould, the pressure was released, and the mould was taken out of the chamber. The pellet obtained was then forced out after the bottom of the mould was removed. In order to prevent damage to the pellet, the mould was carefully removed from the chamber. The depiction of the equipment can be found in Figure 1.

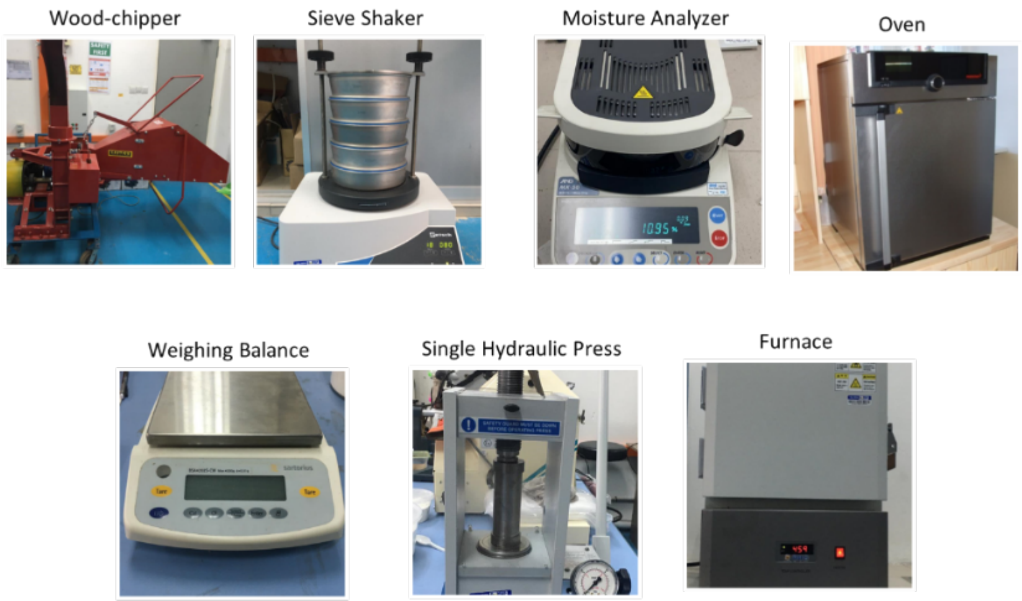

Fig. 1. Equipment involved in the khaya energy pellets production quality

The test for volatile matter was initiated by inserting the sample in a muffle furnace (Brand: Daeyang) at 950 ± 0.5 °C for 7 minutes. After precisely seven minutes, the sample was allowed to undertake a room-temperature cooling procedure. After the temperature of the sample had decreased, it was weighed again to ascertain any weight loss. After subtracting the mass loss due to moisture (A) from the particle sample (B), the volatile matter percentage is calculated. The moisture content of *Khaya senegalensis* was measured using a moisture analyser (Brand: AND MX-50).

$$\text{Weight loss, B (\%)} = (W_i - W_f)/(W_i - W_c) \times 100\%, \qquad \text{Volatile Matter (\%)} = B - A \tag{1}$$

where, Wi = initial weight of the pellet, crucible and cover (g), Wf = final weight of pellet sample (g), and WC = weight of crucible and cover (g).

The determination of ash content involved the measurement of the mass of the residue obtained after subjecting the sample to controlled heating in air, while carefully considering factors such as time, sample weight, and equipment characteristics. The specimen was placed within the furnace and subjected to a heating duration of 60 minutes at an approximate temperature of 700 ± 0.5℃. The experiment involved measuring the initial mass (referred to as mass initial) and the final mass (referred to as mass final) after subjecting the biomass pellets to heating. The ash content percentage in the pellets was then determined using the usual equation.

$$\text{Ash Content (\%)} = (W_3 - W_1)/W_2 \times 100\% \quad (2)$$

where, W_1 = weight of empty crucible (g), W_2 = weight of pellet sample (g) and W_3 = weight of crucible containing the ash (g).

Additionally, this study also assessed the calorific value and fixed carbon content. In proximate analysis, fixed carbon content was calculated as the difference between 100 and the summation of the experimentally recorded percentages of ash content, moisture content, and volatile matter. The estimation of the high heating value (HHV), sometimes referred to as the calorific value, was derived by utilising the correlation presented in Eq. (3) [4]. The equation in question demonstrates a high level of reliability, as evidenced by its R^2 value of 0.827 and a standard deviation of 1.483 MJ/kg. The findings of the conducted experimental proximate analysis in this study were utilised to ascertain the quantities of calorific value.

$$\text{Calorific Value} = 167.2 - 1.449VM - 1.562FC - 1.846ASH \quad (3)$$

where, fixed carbon (FC), volatile matter (VM), and ash (ASH).

3. Results and Discussions

3.1 Ash Content

The ash content of biomass refers to the inorganic minerals and elements that remain after combustion. These minerals are naturally present in biomass and can come from the soil, fertilizers, or other sources. The experimental data in Figure 2 suggests that there is a relationship between the moisture content of khaya pellets and their ash content. Based on the results, we can observe that the ash content of khaya pellets shows some variations with different moisture content levels. The results indicate that as the moisture content increases from 4% to 12%, there is a slight increase in ash content, from 3.75% to 4.09%. This suggests that higher moisture content may be associated with a slightly higher ash content in the khaya pellets. The increase in ash content with higher moisture content could be attributed to several factors.

When biomass with higher moisture content is combusted or thermally converted, more energy is required to evaporate the excess water. The water in the biomass must evaporate during combustion or thermal conversion activities before the real burning may occur. This can result in incomplete combustion and the concentration of ash in the remaining solid material. The presence of water can also affect the combustion process, influencing the temperature and residence time, which can impact ash formation. Additionally, the present results are surprisingly low compared to the ash content of hydrothermally treated biomass feedstock reported in previous study [5], which spans from 6.6% to 16%.

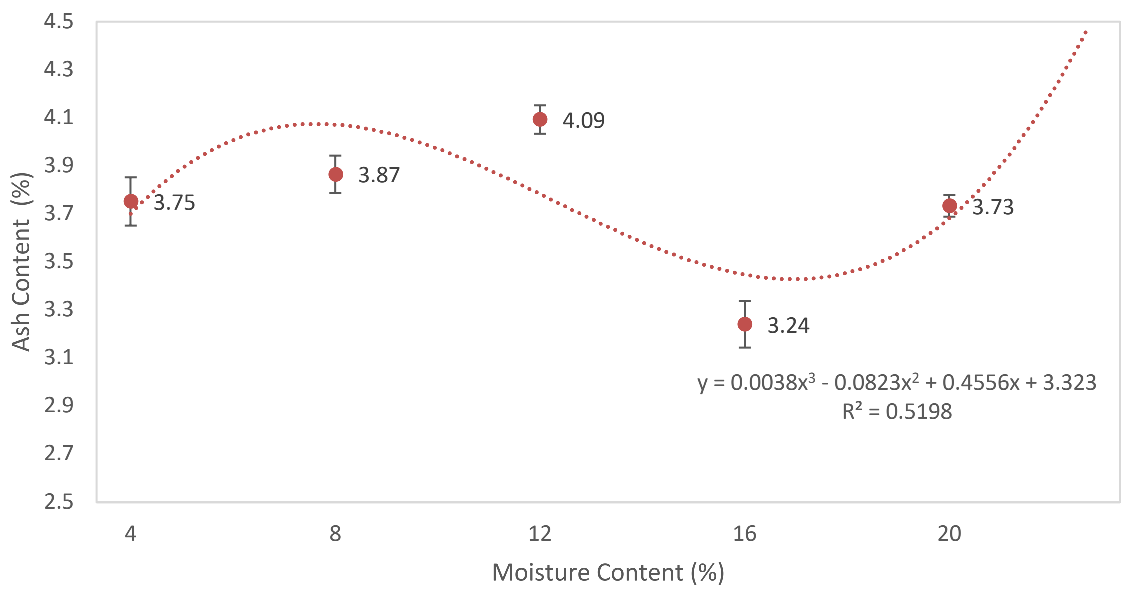

Fig. 2. Effect of feedstock moisture contents on khaya pellets ash content mean

However, an interesting observation is that at 16% moisture content, the ash content decreases to 3.24%, which is lower than the previous moisture content levels. This is because at higher moisture content, the evaporation of water can lead to better temperature control and a more optimal combustion environment, resulting in reduced ash formation. Additionally, the specific characteristics of khaya biomass and its response to varying moisture levels could also contribute to this phenomenon. It is worth noting that at 20% moisture content, the ash content increases slightly to 3.73%. This discovery aligns with the research conducted by [6], which indicated that an increase in moisture content resulted in a reduction of ash quantity.

The combustion process can be influenced by the moisture content of the pellet [7], which in turn affects the temperature of the pellet during combustion. In order to start burning, a pellet may need more heat to remove excess moisture if the moisture content is too high. The supplementary heat demand may give rise to inadequate combustion, thereby causing a higher output of ash. Conversely, in the event that the moisture content is excessively low, the pellet may ignite with excessive rapidity and generate excessive heat, leading to inadequate combustion and an increased production of ash. The optimal moisture content for pellets is subject to variability based on the specific raw material and pelletization methodology employed.

The ANOVA statistical test depicted in Table 1 indicates that this relationship is statistically significant with a p-value less than 0.05 (7.94E-06), which means that the effect of moisture content on ash content is not due to chance.

Table 1
ANOVA results for khaya energy pellet ash content made from several moisture contents

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	512.12	1	512.12	29.79	7.94E-06	4.20
Within Groups	481.35	28	17.19			
Total	993.47	29				

3.2 Volatile Matter

Figure 3 displays the experimental data regarding the volatile matter content of *Khaya senegalensis* pellets that were pelletized using different moisture content levels. The results indicate that the volatile matter content of the pellets ranges from 84.26% to 85.24%. At a moisture content of 4%, the volatile matter content is measured at 85.17%. This value decreases to 85.04% at 8% moisture content, then increases to the maximum value of 85.24% at 12% moisture content. At 16% moisture content, the volatile matter content plummeted drastically to 84.67%, and finally, at 20% moisture content, it reaches 84.26%.

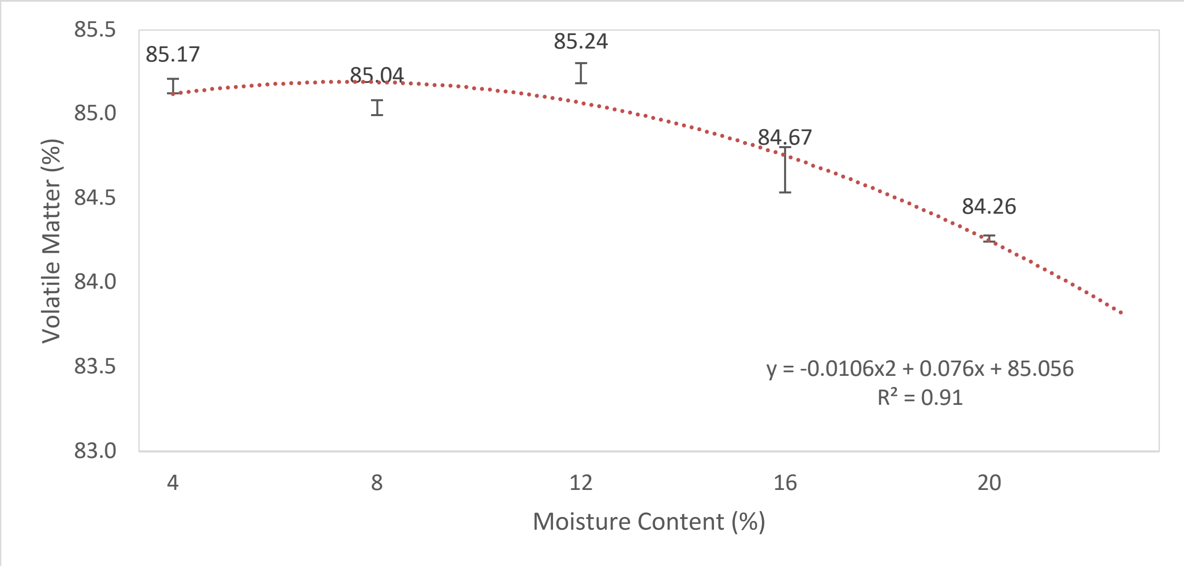

Fig. 3. *Khaya senegalensis* biofuel pellets' volatile matter as a function of moisture content

The data exhibits a quadratic trend in the relationship between moisture content and volatile matter. An R^2 (R-squared) value of 0.91 indicates that 91% of the variance in the volatile matter can be explained by the feedstock moisture content in the regression model. In other words, it suggests that the model is quite effective at explaining the variation in the dependent variable, and it accounts for a significant portion of that variation.

At a moisture content of 4%, the volatile matter content is measured at 85.17%. This initial observation suggests that when the moisture content is relatively low, more of the pellet's composition consists of combustible volatile matter. However, as the moisture content increases to 8%, there is a slight decrease in the volatile matter content to 85.04%. This decline can be attributed to the dilution effect of higher moisture levels, with water contributing to the overall moisture content and reducing the concentration of other volatile components. Remarkably, the data indicates an optimal moisture content level of 12%, where the maximum volatile matter content of 85.24% is achieved. Here, conditions seem ideal for both preserving and enhancing the volatile matter content while maintaining pellet integrity during the pelletization process. In contrast, at 16% moisture content, the volatile matter content experiences a significant drop to 84.67%, emphasizing that excessively high moisture levels can impede the release of volatile matter during combustion. Finally, at 20% moisture content, the volatile matter content further decreases to 84.26%, reinforcing the detrimental impact of excessively high moisture levels on the volatile matter content. This leads to a relatively lower volatile matter content since a smaller portion of the volatile matter is composed of water [8].

Previous researcher [9] determined the optimal moisture content range to produce high quality pellets with high yield ratio and high heating value. The investigation identified that the optimal range for the initial moisture content of rice straw is between 13% and 20%. Hence, it can be hypothesized that this parameter is indeed critical in the production of pellets.

The intricate behaviour observed in the volatile matter content can be attributed to the complex interactions between moisture content, binding capacity, pellet integrity, and the volatilization process during heating. These interdependent factors influence the release and evaporation of volatile matter from the biomass material, ultimately affecting its content in the resulting pellets. These results corroborate the ideas of [10], who suggested that biomass is constantly moist and that this can significantly affect the features and circumstances of fuel ignition. The relationship between moisture content and volatile matter in a substance can be explained by the properties and behaviour of the material when it is heated.

Additionally, it was noted that there is no overlap in the error bars in a Figure 3, it typically indicates a statistically significant difference between the groups or data points being compared. Error bars represent the uncertainty or variability associated with the data points, and no overlap suggests that this uncertainty does not encompass the other group or data point. When error bars do not overlap, it implies that the differences between volatile matter or data points are likely not due to random chance but are statistically significant with changes in moisture content. This absence of overlap in error bars can be an important visual cue when interpreting graphs or charts, as it suggests that there is a substantial and meaningful difference between the compared groups or data sets. This suggests a higher level of confidence in the volatile matter values obtained for those moisture content levels.

To determine the statistical significance of these findings, an ANOVA single-factor analysis was performed, and the results are presented in Table 2. The analysis indicates that the observed differences in volatile matter content among the different moisture content levels are statistically significant, as evidenced by the p-value of 1.86E-28, which is less than the significance level of 0.05. From a scientific perspective, this suggests that moisture content plays a significant role in determining the volatile matter content of *Khaya senegalensis* pellets.

Table 2
ANOVA results for khaya energy pellet ash content made from several moisture contents

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	39834.9	1	39834.90	2311.13	1.86E-28	4.20
Within Groups	482.61	28	17.24			
Total	40317.51	29				

3.3 Fixed Carbon

The experimental data presented in Figure 4 shows the relationship between the moisture content of khaya pellets and their fixed carbon content. Based on the figure, it was found that the equation depicts a quadratic model. A quadratic model relationship trend is a type of non-linear relationship between two variables that is represented graphically as a parabolic curve. This observation implies that as moisture content varies, the fixed carbon content does not change at a consistent rate; rather, it increases or decreases as the moisture content level varies. The coefficient of determination (R^2) for this trend is 0.90, which suggests a strong correlation between the variables. The fixed carbon content of the khaya pellets ranges from 11.01% to 12.0%. The specific fixed carbon percentages for different moisture content levels are as follows: 11.08% for 4% moisture content, 11.10% for 8% moisture content, 11.01% for 12% moisture content, 11.73% for 16% moisture content, and 12.0% for 20% moisture content.

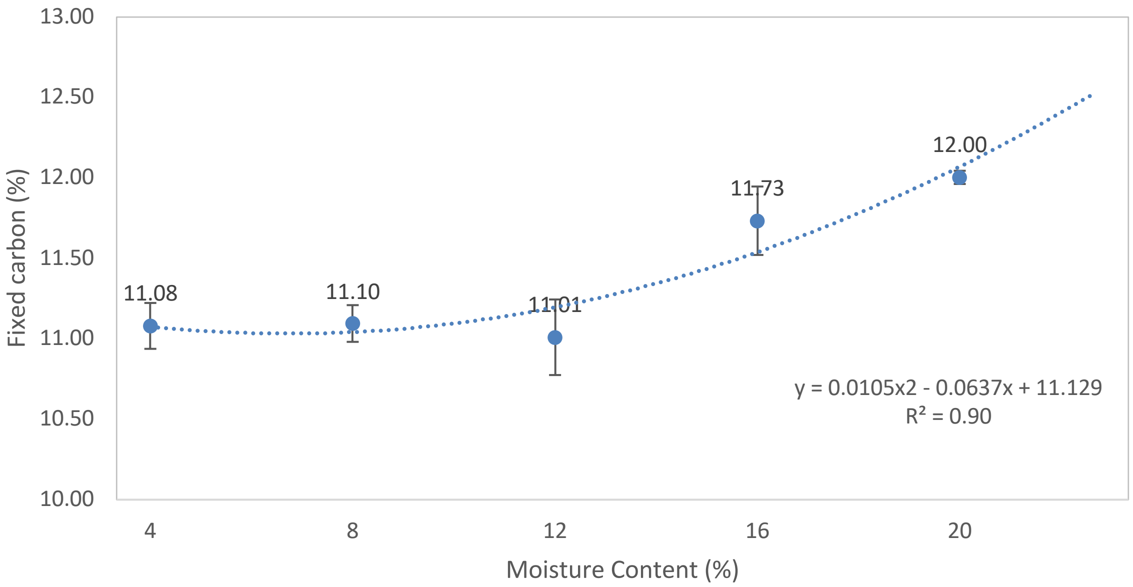

Fig. 4. *Khaya senegalensis* biofuel pellets' volatile matter as a function of moisture content

The fixed carbon refers to the residual fraction of a substance that remains combustible even after the removal of all volatile, organic, and inorganic constituents [11]. The observed outcomes could potentially be attributed to the influence of moisture levels on the chemical constitution of the khaya pellets. As the moisture content increases, it may lead to changes in the composition of the pellets, potentially resulting in higher fixed carbon content. Fixed carbon represents the carbon content available for combustion. Higher moisture content can reduce the efficiency of combustion by requiring additional energy to evaporate the moisture before the carbon can burn [12]. As a result, pellets with lower moisture content may have a higher fixed carbon percentage. On top of that, [13] stated that there is a positive correlation between fixed carbon (FC) and heating value. Accordingly, it should be noted that the moisture content of the initial material has a significant impact on the pelletization process and thermophysical characteristics of pellet [14].

To determine the statistical significance of these results, an ANOVA Single Factor analysis was conducted (Table 3). The analysis indicates that there is no statistically significant difference among the groups. This conclusion is supported by a p-value of 0.69, which is greater than the significance level of 0.05. This outcome suggests that within the range of moisture content tested, variations in moisture content do not have a significant impact on the fixed carbon content of khaya pellets. The lack of statistical significance in the relationship between moisture content and fixed carbon content of khaya pellets could be due to non-linearity in the relationship between moisture content and fixed carbon content. When examining the fixed carbon content, it is important to consider the varying roles that moisture content can play. In a linear relationship, one might expect a consistent incremental or decremental change in fixed carbon content with each incremental change in moisture content. However, biomass materials are complex and heterogeneous, with multiple components that respond differently to changes in moisture. At lower moisture content levels, the composition of the pellets might be dominated by denser and more stable organic matter. However, as moisture content increases, the presence of water can lead to swelling and structural changes in the biomass matrix. This can affect the distribution of organic matter and result in a non-linear relationship between moisture and fixed carbon content. In such cases, the statistical analysis might not be able to capture the complexity of the relationship, leading to non-significant results.

Table 3
ANOVA results for the fixed carbon content of khaya pellets made with different amounts of moisture

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	2.841077	1	2.84	0.16	0.69	4.20
Within Groups	483.2789	28	17.26			
Total	486.12	29				

3.4 Calorific Value

The results pertaining to the calorific value of khaya pellets, which were pelletized from different moisture content, are depicted in Figure 5. The trend observed in this figure shows a polynomial trend, with R^2 of 0.61. The calorific value of the khaya pellets ranges from 19.46 MJ/kg to 19.65 MJ/kg. Specifically, the calorific values for different moisture content levels are as follows: 19.56 MJ/kg for 4% moisture content, 19.51 MJ/kg for 8% moisture content, 19.47 MJ/kg for 12% moisture content, 19.65 MJ/kg for 16% moisture content, and 19.46 MJ/kg for 20% moisture content.

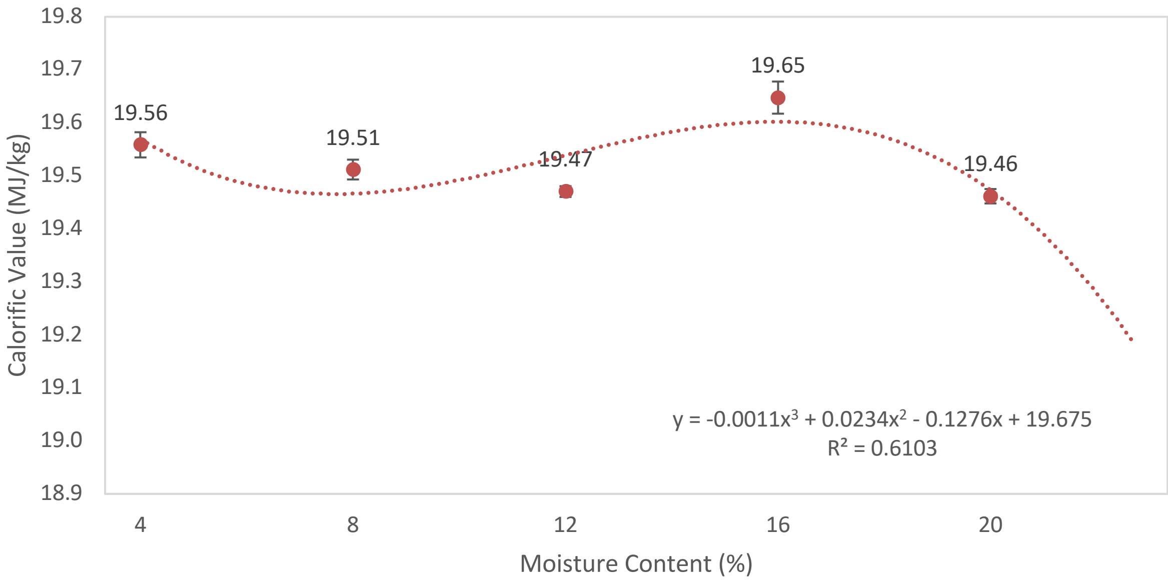

Fig. 5. *Khaya senegalensis* biofuel pellets' calorific value produced at different moisture levels

The polynomial trend observed in calorific value across different moisture content levels, along with an R^2 value of 0.61, suggests that there is a more complex and statistically significant relationship between moisture content and the energy content of Khaya pellets in this study. This means that changes in moisture content are associated with variations in calorific value. A polynomial trend typically implies that the relationship is not linear but follows a curve. In this case, as moisture content increases or decreases from a certain point, it has a noticeable impact on the calorific value. The fact that the trend is not purely increasing or decreasing suggests that there may be an optimal range of moisture content for maximizing calorific value. The highest calorific value (19.65 MJ/kg) was found at the moisture content of 16%.

Generally, when energy pellets have a high moisture content, they tend to have a lower energy density and combustion efficiency, which means that they produce less heat and emit more pollutants when burned. On the other hand, energy pellets with a low moisture content tend to have a higher energy density and combustion efficiency, which means that they produce more heat and emit fewer pollutants when burned. In most cases, higher moisture content leads to a lower calorific value due to the energy required to evaporate the excess moisture during combustion. In this case, the highest moisture content resulted in the lowest calorific value, agrees with the general understanding of moisture content's impact on calorific value. This results in a higher calorific value because there is less water to dilute the energy content. Biomass materials are energy-dense, and the removal of moisture enhances their energy content.

The influence of moisture content on biomass pellet fuel's calorific value and combustion has been extensively studied by [13,14]. It has also been noted that the heating value of biomass declines as its moisture content rises [9]. Moreover, the moisture content of fuel has an impact on its performance. During the combustion process, the moisture present in biomass materials undergoes vaporisation. This leads to an increase in combustion temperature and a reduction in the emission of carbon monoxide (CO) when the resulting carbonised products are combusted, as per previous research [17]. The relationship between the heat value of solid biofuels and moisture content has been found to be inversely proportional [18]. In addition to this, numerous additional researchers have conducted studies on the calorific value using the proximate analysis approach [19-23].

The statistical analysis conducted using ANOVA Single Factor, as shown in Table 4, indicates that the results are statistically significant. This conclusion is supported by a p-value of 2.93E-05, which is less than the significance level of 0.05. The statistically significant results suggest that there are significant differences in calorific value among the different moisture content levels of the khaya pellets.

Table 4
ANOVA results for the calorific value of khaya pellets made with different amounts of moisture

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	425.27	1	425.27	24.90	2.93E-05	4.20
Within Groups	480.16	28	17.19			
Total	905.4314	29				

4. Conclusions

The study on the relationship between moisture content and key properties of Malaysian *Khaya senegalensis* wood pellets has provided valuable insights into their combustion characteristics during thermal conversion. The study analysed ash content, volatile matter, fixed carbon, and calorific value at different moisture content levels, revealing a quadratic trend. The impact of moisture on volatile matter was found to be intricate, with the presence of an optimal moisture content level indicating the desired content. The study revealed that the optimal moisture content for ash content was determined to be 16%, resulting in an ash content of 3.24%. Additionally, a moisture content of 16% was associated with a volatile matter of 85.24% and a fixed carbon content of 12%, which was observed when the moisture content was initially at 20%. Finally, a moisture content of 16% was discovered to yield a calorific value of 19.65 MJ/kg. Moisture content significantly impacts pellet combustion efficiency, with higher moisture content requiring more energy for water evaporation, while low moisture content could lead to excessive heat generation. Fixed carbon content increased with increasing moisture content, suggesting potential changes in pellet composition and chemical constitution. The calorific value initially increased with increasing moisture content, but this deviation may be due to specific factors influencing the experiment. In conclusion, understanding moisture's role in shaping pellet thermophysical characteristics is crucial for efficient and clean combustion, higher energy yields, and improved environmental outcomes. Further research across diverse biomass sources and conditions is necessary to establish more generalized insights. The results of this study provide valuable inputs for optimizing biomass pellet production and enhancing the understanding of energy-related characteristics, contributing to the advancement of renewable energy technologies.

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