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ORIGINAL ARTICLE

Evaluation of *Acacia mangium* Biomass Pellets as Renewable Energy Feedstock Using Proximate, Morphological, and Spectroscopic Analyses

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ABSTRACT - This study evaluates the potential of *Acacia mangium* as a renewable bioenergy feedstock through proximate, calorific, Fourier-transform infrared spectroscopy (FTIR), and scanning electron microscopy (SEM) analyses. Pellets were prepared from stem portions (bottom, middle, and top) at particle sizes of 0.5 mm and 1.5 mm, and characterized for combustion and structural properties. Proximate analysis revealed high volatile matter and moderate fixed carbon, with low ash and moisture content, indicating favorable ignition, sustained burning, and reduced slagging tendencies. Calorific values ranged from 18.27 MJ/kg to 18.74 MJ/kg, demonstrating consistent energy performance across particle sizes and axial positions. FTIR spectra confirmed the preservation of key lignocellulosic structures cellulose, hemicellulose, and lignin with minor modifications in hydroxyl and carbonyl groups after pelletization, supporting efficient combustion behavior. SEM micrographs showed dense fiber packing, reduced porosity, and strong inter-particle bonding, reflecting structural integrity essential for pellet durability and stable burning. The integration of proximate, FTIR, and SEM findings establishes Acacia mangium pellets as a reliable biofuel source with stable chemical, thermal, and morphological properties, reinforcing their role in sustainable energy transitions.

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INTRODUCTION

This growing global need for clean energy has positioned biomass at the forefront of renewable energy studies. Biofuel pellets derived from lignocellulosic feedstocks have gained prominence due to their high energy density, ease of transportation, and potential for reducing greenhouse gas emissions. *Acacia mangium* is an exotic hardwood plant cultivated on a large scale as a timber and pulp crop, but the bioenergy potential has yet to be captured.

Characterization techniques play a key role in determining biomass suitability. Proximate analysis provides general information on fuel quality in terms of moisture, ash, volatile matter, and fixed carbon, which have an immediate impact on combustion efficiency. Scanning Electron Microscopy (SEM) reveals the microstructural pellet morphology, demonstrates surface porosity and compaction quality, and influences burning efficiency. Parallel to this is the Fourier Transform Infrared Spectroscopy (FTIR), which identifies functional groups and chemical bonds that provide information regarding the presence of cellulose, hemicellulose, and lignin, which are necessary for energy output and heat stability [1].

More recent studies have researched biomass characterization and energy exploitation through these techniques. SEM and FTIR, for example, have been used to characterize nanostructured sorbents from rice husks in order to determine porosity and functional group composition [2]. FTIR spectroscopy, particularly,

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has improved the identification of biomass chemical structures [3]. Moreover, biofuel policy and production research emphasize the growing significance of biomass fuels in replacing fossil fuels [4].

Despite such advances, explicit research on *Acacia mangium* biofuel pellets is scarce. Most of the research has been focused on agricultural waste such as rice husk, corn cobs for biofuel or material purposes [5]. Insufficient research integrates proximate, morphological, and spectroscopic analyses for *Acacia mangium* alone, producing a deficiency of information regarding its fuel efficiency, combustion stability, and structural suitability as pelletized biofuel. While SEM and FTIR have been widely used in biomass characterization, their application to *Acacia mangium* pellets remains limited. No comprehensive study combining proximate analysis, SEM, and FTIR exists to fully establish its fuel quality, microstructure, and chemical functionality. Addressing this gap will help determine the viability of *Acacia mangium* as a sustainable bioenergy feedstock, supporting renewable energy transitions in tropical regions.

Currently, no study has systematically combined proximate, morphological, and spectroscopic evaluations to comprehensively characterize *Acacia mangium* pellets. Such integration is essential: proximate analysis determines combustion efficiency and fuel quality; SEM reveals microstructural integrity and densification behavior; while FTIR identifies functional group stability and chemical transformations during pelletization. By uniting these analytical perspectives, the present study provides the first holistic assessment of *Acacia mangium* pellets as a renewable bioenergy feedstock, addressing a critical knowledge gap and establishing a foundation for future bioenergy research on tropical hardwoods

MATERIALS AND METHODOLOGY

Sample Preparation

Acacia mangium trees with diameters of 5–8 cm were selected. Each stem was longitudinally segmented into three axial portions: bottom (50%), middle (30%), and top (20%). The segments were debarked, split into billets. Billets were processed through a multi-stage size reduction. Wood was first chipped into 5–10 cm fragments using a drum chipper, shredded, and crushed to 1–2 cm pieces. Final grinding with a disc mill produced fine particles in two fractions: ≤0.5 mm and ≤1.5 mm. The ground material was dried to a moisture content of 16–18% using a calibrated moisture analyzer. Oversized particles and contaminants were removed via screening, after which the material was air-dried, separated by size, and labelled.

Pelletization and Analysis

Prepared particles were pelletized using a flat-die pellet mill. The resulting pellets were characterized through proximate analysis, scanning electron microscopy (SEM), and Fourier-transform infrared spectroscopy (FTIR). Proximate analysis followed standardized procedures, with a summary provided in Table 1. While moisture content were calculated using Equation 1, where W1 is the initial mass of the sample before drying (g) and W2 is the final mass of the sample after drying (g). Three replicates of the sample were prepared for each test shown in Table 1.

Table 1. Summary of Proximate Test Pellet Testing

Test	Proximate Test	
	Standard Procedure	Unit
Moisture Content	IS CEN/TS 14774-1:2004 ASTM E871-82 EN 14774-2:2009	%
Ash Content	IS CEN/TS 14775:2004 ASTM D1102-84 EN 14775:2009	%
Volatile Matter	IS CEN/TS 15148:2005 ASTM D3175-20	%
Fixed Carbon	IS CEN/TS 15148:2005 ASTM D3175-02	%

$$\frac{W1 - W2\ (g)}{W1(g)}\ x\ 100 \qquad \text{(Eq. 1)}$$

Ash Content

During proximate analysis, one of the key products obtained is inorganic ash. After determining volatile matter, the remaining sample is further heated in the presence of oxygen, allowing the residual carbon to oxidize into carbon dioxide, leaving only the inorganic fraction as ash. Ash content is expressed as the percentage of non-combustible residue present in the fuel after complete combustion. This parameter is critical because it influences the combustion efficiency of the pellets, reflecting both the proportion of incombustible matter and the energy loss associated with it. The ash determination is performed immediately after the volatile matter test, using the residual sample from that stage. The resulting ash percentage is calculated using Equation (2), where the initial volatile mass corresponds to the mass of the sample after the volatile test.

$$\frac{\text{mass of residue (g)}}{\text{initial volatile mass (g)}}\ x\ 100 \qquad \text{(Eq. 2)}$$

Fixed Carbon

The fixed carbon was the amount of carbon product created after the burner process. It was important to indicate that the carbon emission of the pellet was compromised. The total weight (100 %) of the pellet sample measured before the burning process was subtracted from all the combinations of the after-burner product. The following equation shows the calculation of fixed carbon. Analysis was done according to the standard procedure ASTM 5142-09 [6]. Equation 3 shows the calculation for fixed carbon.

$$100(\%) - [M\ C\ (\%) + VM\ (\%) + Ash\ (\%)] \qquad \text{(Eq 3)}$$

Volatile Matter

Volatile matter constitutes a significant fraction of biomass and plays an essential role in the design and operation of burners and gasifiers. When biomass is heated in an inert atmosphere at approximately 400 °C, the volatile components decompose, releasing various gaseous products. The material remaining after this thermal treatment consists of a mixture of fixed carbon and ash. Determination of volatile matter follows the ASTM D5142-09 [6] standard procedure. After heating, the sample is reweighed to measure the mass of the remaining residue (g), which represents the volatile fraction. The percentage of volatile matter is then calculated using the appropriate formula shown in Equation 4

$$\frac{\text{Initial mass(g)} - \text{Mass of residues (g)}}{\text{Initial Mass (g)}}\ x\ 100 \qquad \text{(Eq. 4)}$$

Moisture Content

The moisture content of the fuel sample represented the amount of water, as presented in the pellet sample. Moisture content is important to make a suitable environment for the pellet because the moisture content influences the pellet stability, in terms of shape and form. Besides, the moisture content must be standardized for an easy exportation process all over the world, without damaging the quality of the pellet produced. Analysis according to the standard procedure [6].

Lignocellulosic Biomass

The calorific value represents the amount of heat energy released by wood pellets during complete combustion and is a key indicator of their fuel quality. A higher heating value signifies greater potential for commercial energy applications, reflecting the suitability of the biomass source. Factors such as tree species, axial portion of the stem, particle size, and blending ratios are major determinants of calorific performance. In this study, the calorific value of Acacia mangium pellets was measured using a bomb calorimeter, with results expressed in joules per kilogram (J/kg) to quantify the energy released. The analysis was conducted by the [7] standard procedure.

FTIR Analysis

Fourier transform infrared analysis (FTIR) was performed to study the chemical structure of organic molecules and to detect potential structural changes. Spectra were viewed using a Perkin-Elmer Spectrometer supplied by Perkin-Elmer Company from Bridgeport, USA. The spectra of the samples were obtained by averaging 15 scans with a wavenumber range between 4000 cm^{-1} and 650 cm^{-1} with a resolution of 2 cm^{-1}. Each piece was mixed with KBr and pressed into a disk with a ratio of 1:100. In infrared spectroscopy, the radiation of infrared light (IR) is passed through the piece.

Scanning Electron Microscopy

Scanning electron microscopy (SEM) was employed as part of the morphological characterization of the composite samples. Test specimens measuring 1cm x 1cm x 1cm were prepared from the internal bonding strength samples. Before imaging, the specimens were thoroughly cleaned to remove any contaminants and oven-dried at 105 °C. To enhance conductivity, the samples were coated with a thin layer of gold (approximately 20 nm in thickness) using a POLARON 515 sputter coater. Imaging was carried out using a LEO Supra 50 variation pressure (VP) scanning electron microscope manufactured by Carl Zeiss, Oberkochen, Germany, which was connected to a computer for image acquisition and processing. SEM images were evaluated based on surface morphology and analyzed from various preferred angles

RESULTS AND DISCUSSION

Proximate Analysis

The proximate analysis of *Acacia mangium* pellets revealed relatively stable values across different particle sizes and stem portions, indicating uniform combustion properties. Table 1 shows the result of proximate analysis of *Acacia mangium* pellet. Volatile matter constituted the largest fraction, followed by fixed carbon, while ash content and moisture were comparatively low. This distribution suggests that *Acacia mangium* pellets possess favorable fuel characteristics since higher volatile matter promotes ease of ignition and efficient burning. At the same time, the presence of fixed carbon supports sustained combustion.

Conversely, low ash content is advantageous because it minimizes slagging and fouling during combustion, improving boiler efficiency and reducing maintenance requirements. Comparable results have been reported for woody biomass, where volatile matter values exceeding 70% and ash content below 5% were identified as optimal for pelletized fuels [8]. Moreover, the observed proximate composition aligns with the findings by İnsel et al. [9], who demonstrated that volatile-rich biomass enhances the predictability of calorific value and combustion performance.

Similarly, Mondal and Rafizul [10] emphasized that proximate fractions are strong indicators of heating potential and are critical for optimizing thermochemical conversion pathways. Recent investigations on biomass fuel blends also confirmed that maintaining low ash and moderate moisture levels improves energy efficiency and reduces greenhouse gas emissions during combustion [11].

Collectively, the proximate results of *Acacia mangium* pellets highlight their suitability as a bioenergy resource, demonstrating consistent fuel quality across processing variables, which supports their potential for large-scale renewable energy applications.

Table 1. Proximate analysis result of *Acacia mangium* pellet

Stem Portion	Particle Size (mm)	Moisture (%)	Volatile Matter (%)	Fixed Carbon (%)	Ash (%)
Bottom	0.5	3.21±0.8	83.4±2.7	83.69±2.5	0.26±0.15
	1.5	2.64±0.5	80.29±0.5	83.69±0.6	0.21±0.05
Middle	0.5	4.02±1.9	81.36±0.7	83.69±1.6	0.47±0.4
	1.5	1.12±0.3	80.82±0.3	83.69±0.4	0.08±0.4
Top	0.5	2.52±0.3	82.28±1.3	83.69±1.1	0.21±0.08
	1.5	2.01±1.1	80.51±0.3	83.69±0.9	0.17±0.1

Calorific Value Analysis

The evaluation of calorific values in *Acacia mangium* pellets shows that the energy content remains relatively stable across different particle sizes and pellet segments shown in Figure 1, with values ranging from 18.27 MJ/kg to 18.74 MJ/kg. At the bottom portion, the calorific value was 18.27 MJ/kg for 0.5 mm particles and slightly higher at 18.36 MJ/kg for 1.5 mm, indicating a modest improvement with increased particle size. In the middle section, values rose to 18.38 MJ/kg (0.5 mm) and 18.58 MJ/kg (1.5 mm), suggesting that coarser particles may enhance energy output. At the top portion, the calorific value peaked at 18.74 MJ/kg (0.5 mm) and 18.73 MJ/kg (1.5 mm), demonstrating that particle size had minimal influence in this section.

Overall, the findings confirm that *Acacia mangium* pellets provide dependable calorific performance with only slight fluctuations due to particle size or pellet portion, reinforcing their potential as a consistent and renewable energy source. Supporting this, Pambudi & Saechua [12] developed a near-infrared spectroscopy model to predict the heating value of *Acacia mangium*, reporting results close to 19 MJ/kg, underscoring its suitability as an energy crop. Likewise, Zhang [13] highlighted the broader role of biomass energy in lowering greenhouse gas emissions and strengthening energy security through both thermochemical and biochemical conversion processes. Wu [14] further emphasized how emerging biomass technologies, such as pyrolysis and gasification, can maximize energy recovery and material utilization. Despite this progress, most prior studies on *Acacia mangium* have focused on fiber properties for industrial applications like papermaking [15].

This presents a significant gap in knowledge, as integrating physicochemical and structural evaluations would provide a more complete understanding of fuel quality, combustion behavior, and optimization opportunities. Addressing this shortfall is crucial for advancing the utilization of *Acacia mangium* in sustainable bioenergy systems.

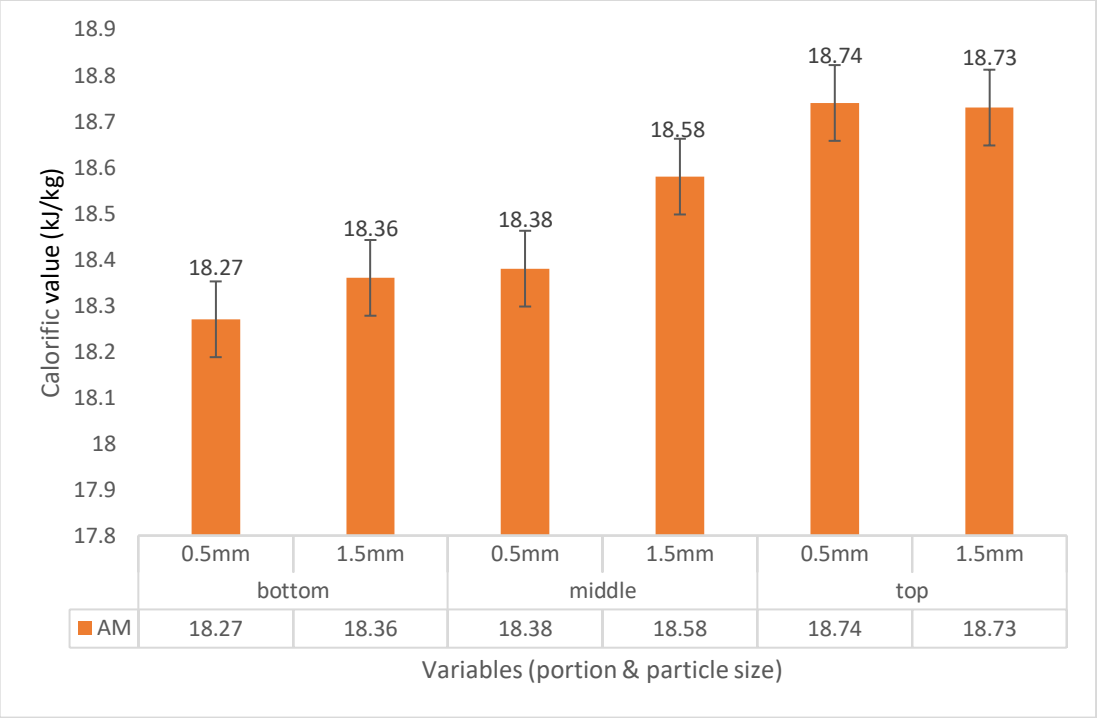

Figure 1. Calorific value of *Acacia Mangium* pellet.

Fourier Transform Infrared (FTIR) Analysis

The FTIR spectra of *Acacia mangium* in both raw and pelletized with top region and particle size 0.5mm, reveal functional groups typical of lignocellulosic biomass. As shown in Figure 2, the broad absorption around 3300 cm^{-1} corresponds to O–H stretching vibrations in cellulose and hemicellulose. A slight reduction in intensity after pelletization suggests minor dehydration and partial structural modification. The peaks near 2900 cm^{-1}, assigned to C–H stretching in aliphatic groups, remain largely unchanged, indicating that densification does not significantly affect the hydrocarbon backbone. A distinct band near 1700 cm^{-1}, attributed to C=O stretching in hemicellulose and lignin, is more prominent in pellets, likely due to thermal reconfiguration during compaction. Vibrations within 1500–1600 cm^{-1} confirm aromatic skeletal structures of lignin, while strong bands between 1000–1100 cm^{-1} represent polysaccharide C–O–C stretching, highlighting the preservation of cellulose. These spectral patterns align with earlier reports showing that pelletization introduces only minor adjustments in hydroxyl and carbonyl groups while maintaining cellulose and lignin stability [16-17].

Proximate analysis further validates these structural observations, demonstrating consistent volatile matter, fixed carbon, ash, and moisture content across particle sizes and stem sections, underscoring the suitability of *A. mangium* pellets as a biofuel. Elevated volatile matter and moderate fixed carbon indicate efficient ignition and sustained combustion, while the low ash fraction suggests reduced slagging potential. These combustion properties directly correspond to FTIR findings: hydroxyl and polysaccharide peaks confirm intact cellulose and hemicellulose that drive volatile release, while stable aromatic and carbonyl vibrations reflect lignin's contribution to fixed carbon and long burning duration. The slightly stronger carbonyl peak in pellets indicates structural rearrangements during densification that enhance compactness without degrading chemical integrity. Similar associations between FTIR features and proximate results have been noted in other biomass pellet studies, emphasizing the importance of stable lignocellulosic bonds for reliable combustion [18-19].

Overall, the integration of proximate and FTIR analyses demonstrates that *Acacia mangium* pellets maintain their biochemical integrity while offering predictable fuel performance. This structural stability underpins not only efficient combustion but also pellet durability, as highlighted in recent studies [20]. Comparable FTIR patterns in other woody biomasses confirm that pelletization primarily improves densification and handling properties while preserving fundamental chemical composition [18-19]. Consequently, the results confirm the potential of *Acacia mangium* pellets as a sustainable bioenergy resource with stable combustion behavior.

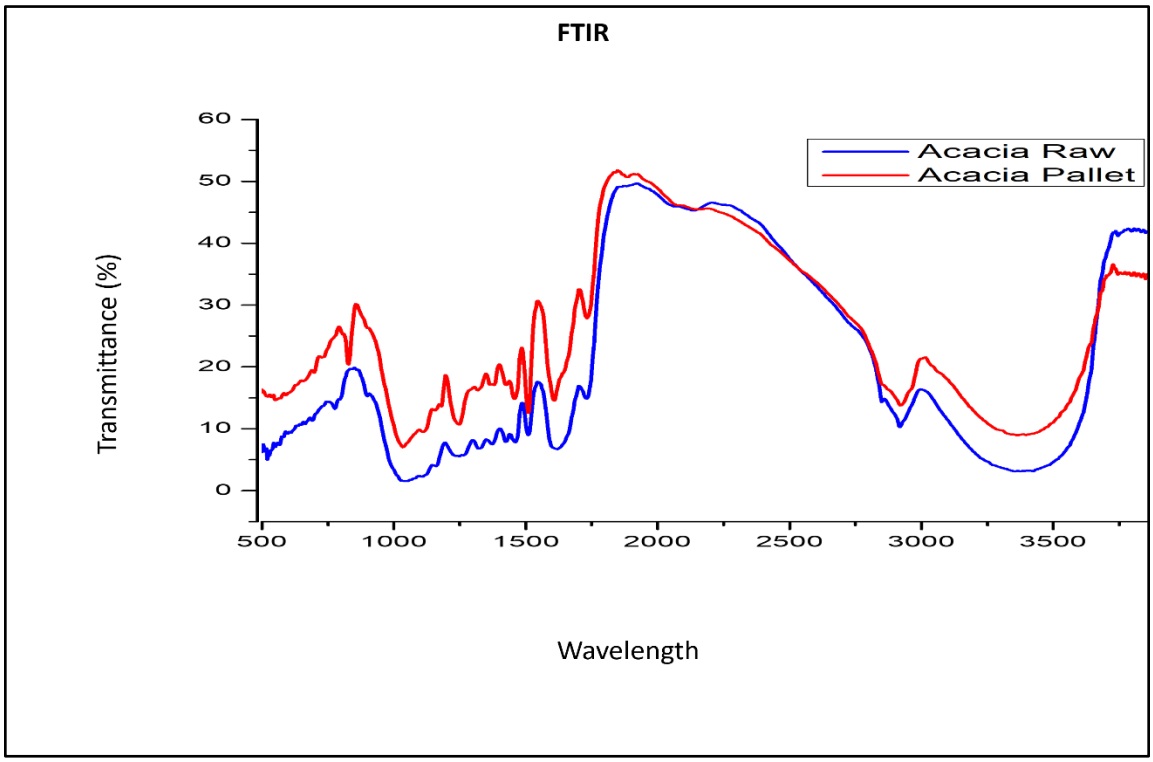

Figure 2. FTIR of Acacia mangium pellet.

Morphological

The SEM micrograph of *Acacia mangium* pellets at 0.5 mm particle size (bottom section, 500× magnification) shown in Figure 3 reveals a compact and fibrous structure with well-aligned cell wall arrangements and partially fractured surfaces. The visible fibrils and layered morphology indicate that pelletization effectively compressed the biomass particles, enhancing inter-particle bonding and reducing porosity. Such structural densification is critical in improving bulk density, mechanical strength, and combustion efficiency of biomass pellets [21]. The smooth and continuous regions suggest good thermal softening of lignin, which acts as a natural binder during densification, while the presence of minor cracks and debris reflects localized stresses from compaction.

Microstructural characteristics observed here strongly correlate with the proximate and FTIR analyses. The dense fiber packing supports low moisture content and reduced pore volume, thereby contributing to higher calorific value and improved combustion stability. Furthermore, the intact fibrous bundles, rich in cellulose and hemicellulose, align with the FTIR peaks around 1000–1100 cm^{-1}, confirming preserved polysaccharide networks that promote volatile release during pyrolysis. Meanwhile, the compactness of the

lignin-rich domains, observed as darker rigid layers, is consistent with FTIR aromatic skeletal vibrations (1500–1600 cm^{-1}), which sustain fixed carbon content and prolong combustion.

Similar findings have been reported in SEM analyses of woody biomass pellets, where microstructural densification was linked to reduced ash content, higher mechanical durability, and uniform combustion performance [22]. More recent investigations also emphasize that fine particle sizes, such as the 0.5 mm fraction used here, favor stronger inter-fiber bonding and higher density, leading to improved thermal behavior [23]. Thus, the SEM evidence confirms that *A. mangium* pellets possess favorable microstructural integrity, which complements the proximate and FTIR results, reinforcing their potential as a high-quality biofuel.

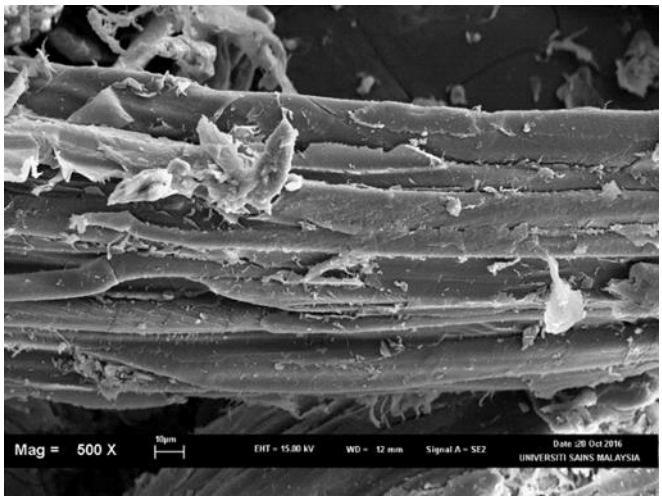

Figure 3. SEM of 0.5mm bottom Acacia mangium with 500x magnification.

The scanning electron microscopy (SEM) image in Figure 4 presents the microstructural morphology of the bottom surface of a 1.5 mm thick *Acacia mangium* wood sample at a magnification of 500×. The image reveals distinct anatomical features characteristic of both softwood and hardwood species, with a particular emphasis on cellular arrangement and surface topography. At this magnification, the layered structure of the wood is clearly visible, showcasing the alignment of cellulose fibers and the presence of parenchyma cells, vessels, and pits [24].

The observed stratified pattern reflects the natural growth rings and the radial alignment of tracheids and fiber cells, which are typical in *Acacia mangium*, a fast-growing tropical hardwood. The surface exhibits a relatively smooth but undulating texture, with evidence of cell wall undulations and intercellular spaces. The presence of numerous small, circular pits likely representing pit fields between adjacent cells suggests efficient water transport and structural integrity within the tissue. These pits are evenly distributed across the surface, indicating well-developed intercellular connections that contribute to mechanical strength and fluid movement.

The overall morphology suggests that the bottom surface has undergone minimal degradation, as no significant cracks, delamination, or fungal colonization were observed. However, minor surface irregularities may indicate early-stage drying stress or mechanical handling during sample preparation. The absence of severe defects implies good structural integrity, making *Acacia mangium* a promising candidate for engineered wood products and bio-based composites.

In conclusion, the SEM micrograph provides critical insights into the microstructure of *Acacia mangium*, highlighting its cellular organization and surface characteristics. These morphological features are crucial for understanding the material's performance in applications such as biomass conversion, pulp and paper production, and sustainable construction materials. Future studies could explore higher

magnifications to examine nanoscale fibrillar structures and lignin distribution, further enhancing our knowledge of this versatile tropical timber.

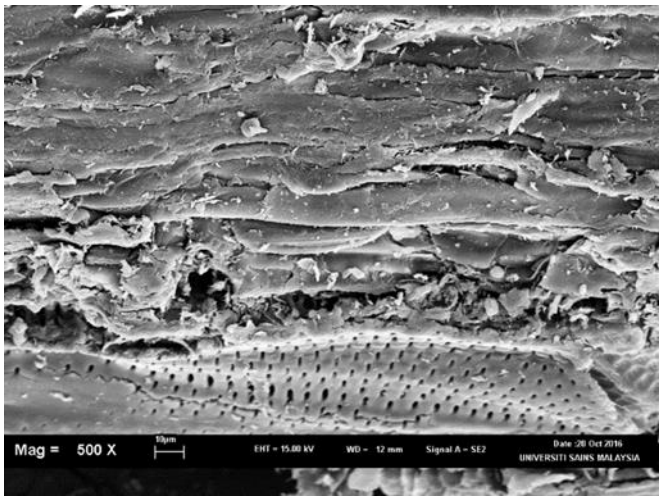

Figure 4. SEM of 1.5mm bottom Acacia mangium with 500x magnification

CONCLUSION

The comprehensive evaluation of *Acacia mangium* pellets demonstrates their strong potential as a sustainable bioenergy resource. Proximate analysis confirmed favorable fuel quality, with high volatile matter, sufficient fixed carbon, and minimal ash factors that collectively enhance ignition, combustion stability, and overall efficiency. Calorific value results (18.27–18.74 MJ/kg) further underscore the reliability of *Acacia mangium* pellets as a consistent energy source across particle sizes and stem sections. FTIR analysis verified that pelletization preserved essential lignocellulosic structures, while SEM observations confirmed dense microstructural arrangements, strong inter-fiber bonding, and reduced porosity, all of which contribute to mechanical durability and stable combustion performance. Looking forward, future research should extend these findings by incorporating thermogravimetric and kinetic analyses to better understand combustion dynamics and optimize processing conditions. Additionally, life-cycle assessment (LCA) and techno-economic evaluation will be crucial in determining the environmental and financial feasibility of large-scale pellet production. On a practical level, *Acacia mangium* biomass could be utilized in co-firing systems, rural micro-grids, or industrial boilers, supporting energy diversification and carbon neutrality initiatives in tropical regions. With its stable physicochemical and structural attributes, *Acacia mangium* stands as a promising feedstock for the development of next-generation bioenergy technologies and sustainable fuel systems in Southeast Asia and beyond.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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