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Comparative Study on the Anatomical Features and Chemical Composition of *Leucaena leucocephala* Wood for Pulp and Paper Application

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ABSTRACT

Leucaena leucocephala, locally known as "petai belalang," is widely found in Malaysia and utilised for forage, reforestation, and as a source of timber for furniture and construction. This study aims to identify and compare the anatomical properties, chemical composition, and wood density of *L. leucocephala* at three stem positions (top, middle, and bottom). Wood samples aged 3–5 years were collected from the Universiti Malaysia Kelantan area. Anatomical characteristics were assessed by measuring fibre length, fibre diameter, and lumen diameter. Chemical composition analyses, including lignin, hemicellulose, α-cellulose, holocellulose, and extractives, were conducted following TAPPI standards. Results indicated that the bottom section had the highest mean fibre length (1072.5 µm), lowest fibre diameter (22.0 µm), and the thinnest fibre wall (1.35 µm). The middle section exhibited the most favourable chemical properties, with the highest hemicellulose content (18.44%), lowest lignin content (28.96%), and moderate extractives (1.12%). Holocellulose was highest at the bottom (68.79%), followed by the middle (67.24%) and top (65.62%). Regression analysis showed that fibre length is a more reliable predictor of pulp and paper strength than wood density. These findings suggest that *L. leucocephala*, particularly from the bottom and middle sections, holds strong potential for pulp and paper applications.

Keywords: fiber morphology; tropical fast-growing species; pulp quality

1. Introduction

Paper production relies on fibres that undergo chemical and mechanical treatments, meaning plant-based raw materials do not have a fixed chemical composition but rather one largely determined by the fibre source [1]. The primary method of assessing paper pulp quality involves converting the pulp into paper and evaluating its properties [2]. Given that the pulp and paper industry is highly energy-intensive, reducing energy consumption is crucial for maintaining competitiveness in the global market [3]. Enhancing knowledge of pulp suspension behaviour can improve process control and enable better predictions of paper strength and quality [4].

Paper production involves chemically treating pulpwood, typically with alkalis or bisulfites, to degrade lignin, followed by pressing the resulting pulp into a web of cellulose fibres [5]. The mechanical and strength characteristics of paper are influenced by the chemical composition, morphology, and structural attributes of individual fibres, as well as chemical changes that impact the paper's long-term stability [6]. These strength properties are key indicators of paper durability. Although comprehensive evaluation of wood properties provides the most accurate prediction of pulp yield and paper strength, such assessments are often resource-intensive and time-consuming [7]. Direct pulping trials, in particular, demand substantial materials and labour. In contrast, anatomical parameters like fibre dimensions offer a more practical and cost-effective means for estimating pulp and paper quality.

Leucaena leucocephala, a species under the Leguminosae family, has gained attention as a potential raw material for the pulp and paper industry. While Acacia species are widely used in paper production, limited research exists on the anatomical properties and chemical composition of *Leucaena leucocephala* [2]. This species is cultivated for various purposes, including paper production, and its use as pulpwood could support local industries in developing countries where demand for paper is increasing [3]. However, further testing is needed to determine its suitability for pulping and paper-making.

This study aims to address the knowledge gap by investigating the anatomical properties, chemical composition, and wood density of *Leucaena leucocephala* at different positions within the tree. By identifying and comparing these properties across different positions, the findings may provide valuable insights into the potential of *Leucaena leucocephala* as an alternative raw material for pulp and paper production. A better understanding of these factors could contribute to sustainable paper manufacturing by identifying alternative fibre sources, reducing deforestation, and promoting the cultivation of suitable tree species [5]. Additionally, the study could be useful for paper manufacturers seeking cost-effective and high-quality raw materials for optimised production processes [6].

2. Materials and Methods

2.1 Materials and Preparation

The study was conducted using *Leucaena leucocephala* wood samples collected from areas surrounding Universiti Malaysia Kelantan. This species was selected due to its abundance in Malaysia, particularly in rural communities where it is commonly utilised for both culinary and medicinal purposes. Trees aged between 3 and 5 years were randomly selected, and 10 cm-thick discs were extracted from three different stem positions—top, middle, and bottom—to examine variation along the vertical axis.

Each disc was used to assess anatomical characteristics, chemical composition, and wood density. Three replicates were prepared for each test to ensure the reliability and representativeness of the results, in accordance with the procedures adapted from Yahya et al. [8].

The materials used for sample preparation and analysis included *L. leucocephala* wood, acetic acid, 30% hydrogen peroxide, safranin, ethanol, sodium chlorite, sodium hydroxide, sulfuric acid, and distilled water. An ice bath was also employed where necessary to maintain appropriate reaction conditions. These reagents facilitated both the anatomical staining and chemical extraction processes required for comprehensive wood characterisation.

2.2 Anatomical Properties

2.2.1 Determination of fibre dimension

To determine the anatomical properties, wood cubes measuring 2 × 2 × 2 cm were prepared from each disc, representing the top (T), middle (M), and bottom (B) sections of the stem. Smaller chips measuring approximately 1 × 0.2 × 0.2 cm were further extracted from these cubes for fibre dimension analysis, following the method described by Yahya et al. [8].

The specimens were macerated in a 2:1 solution of acetic acid and hydrogen peroxide at 60 °C for 48 hours. After maceration, the fibres were thoroughly rinsed with distilled water at least three times. The cleaned fibres were

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then transferred into a clean container, and a few drops of safranin were added to stain the samples. The container was gently shaken to allow for proper dispersion and separation of the fibres.

A portion of the stained fibre suspension was mounted on a microscope slide for analysis. Using a calibrated light microscope, key anatomical parameters were measured, including fibre length, fibre diameter, lumen diameter, and cell wall thickness [8][9]. The cell wall thickness was calculated using the formula:

$$\text{Cell wall thickness} = \frac{\text{Fiber diameter} - \text{Lumen diameter}}{2} \quad (1)$$

The data obtained were arranged arithmetically, and derived anatomical values were calculated based on standard formulas referenced in [8].

$$RR = \frac{FWT^2}{FLD} \quad (2)$$

$$MR = \frac{FD^2 - FLD^2}{FD^2} \quad (3)$$

$$SR = \frac{FL}{FD} \quad (4)$$

$$CR = \frac{FWT}{FD} \quad (5)$$

$$FC = \frac{FLD}{FD} \quad (6)$$

Where:

RR= Runkel ratio; MR= Muhlstepth's ratio; SR= Slenderness ratio; CR= Coefficient of rigidity; FC = Flexibility coefficient; FL= Fiber length; FD= Fiber diameter; FWT= Fiber wall thickness; FLD = Fiber lumen diameter

2.3 Chemical Composition

2.3.1 Determination of extractives

Wood discs were collected from the top, middle, and bottom parts of each tree, with three replicates prepared for each section. From each disc, cubes measuring 2.5 × 2.5 × 2.5 cm were cut at the boundary between heartwood and sapwood for chemical composition analysis. These cubes were chipped using a knife and further ground into coarse particles using a grinder.

The chemical composition of the samples—including extractives, lignin, hemicellulose, and α-cellulose—was determined following TAPPI standards T 204, T 222, T 9, and T 203, respectively [8]. For extractives analysis (TAPPI T 204 cm-07), approximately 5 g of ground sample was placed in a cellulose extraction thimble and extracted with 300 ml of a 2:1 ethanol-toluene solution for 8 hours.

The extract was collected in a pre-weighed flask, and excess solvent was removed using a rotary evaporator. The flask was then dried in an oven at 103 ± 2 °C for three days. After drying, it was transferred to a desiccator for 30 minutes, allowed to cool, and weighed again. The extractive content was calculated using the following formula:

$$\text{Extractive content (\%)} = Wa/Wb \times 100\% \quad (7)$$

Where Wa is the extractives weight, and Wb is oven oven-dried weight of respective sample particles

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2.3.2 Determination of holocellulose

Extractive-free wood particles were used for holocellulose determination. Approximately 2 g of the sample was placed in a 250 ml conical flask. Then, 100 ml of distilled water, 1.5 g of sodium chlorite, and 5 ml of 10% acetic acid were added. The mixture was placed in a shaking water bath at 70 °C and shaken for 30 minutes.

After the first 30 minutes, an additional 5 ml of 10% acetic acid was added, and shaking continued for another 30 minutes. This was followed by the addition of another 1.5 g of sodium chlorite. This alternating addition of acetic acid and sodium chlorite was repeated every 30 minutes until a total of 6 g of sodium chlorite had been added. After the final addition, the mixture was heated for an additional 30 minutes.

The flask was then removed and cooled in an ice bath. The holocellulose was filtered using a pre-weighed crucible (No. 2), washed thoroughly with cold distilled water, followed by acetone, and then dried. The crucible containing the holocellulose was oven-dried at 103 ± 2 °C for three days.

The holocellulose content was calculated using the formula:

$$\text{Holocellulose content (\%)} = (Wa/Wb \times 100\%) \times ((100-ec)/100 \quad (8)$$

Where Wa is the holocellulose weight, Wb is the oven-dried weight of the extractive-free sample particle, and ec is the extractive content.

2.3.3 Determination of α-cellulose

The α-cellulose content was determined following TAPPI T203 cm-09 by selectively removing hemicellulose using 17.5% sodium hydroxide. Approximately 1 g of holocellulose (from the previous procedure) was placed in a 250 ml beaker, and 7.5 ml of 17.5% NaOH (pre-cooled to 20 °C) was added. The mixture was maintained at 20 ± 1 °C in an ice-cooled water bath and gently stirred with a glass rod for 1 minute.

Subsequently, 5 ml of 17.5% NaOH was added and stirred for 45 seconds, followed by another 5 ml stirred for 15 seconds and then left undisturbed for 3 minutes. An additional 5 ml of NaOH was added every 150 seconds, repeated three times. The mixture was then left to stand for 30 minutes.

Afterwards, 50 ml of distilled water (20 °C) was added and stirred vigorously for 30 minutes. The mixture was filtered through a pre-weighed crucible (No. 3) using vacuum suction. To ensure complete transfer, the beaker was rinsed with 12.5 ml of 8.3% NaOH. The retained α-cellulose was washed with 325 ml of distilled water (20 °C), and 7.5 ml of 10% acetic acid was added to the crucible and allowed to stand for 5 minutes to neutralise any remaining alkali. The acetic acid was removed by suction, and the sample was washed again with distilled water.

The crucible containing the α-cellulose was dried in an oven at 103 ± 2 °C for three days. The α-cellulose content was calculated using the formula:

$$\text{α-cellulose content (\%)} = (Wa/Wb \times 100\%) \times (((100-h))/100) \quad (9)$$

Where Wa is the α-cellulose weight, Wb is the oven-dried weight of the extractive-free sample particle, and h is the holocellulose content.

2.3.4 Determination of lignin and hemicelluloses

Lignin content was determined using the Klason method, following TAPPI T 222 om-11. Approximately 1 g of extractive-free wood particles (prepared as described in the extractive determination procedure) was placed in a 150 ml beaker and maintained in a water bath at 20 ± 1 °C. A volume of 15 ml of cold 72% sulfuric acid was added to the beaker, and the mixture was stirred gently using a glass rod to ensure thorough mixing. The sample was allowed to stand in the water bath for 2 hours for hydrolysis.

A 1000 ml conical flask was prepared with 560 ml of distilled water. The acid-treated mixture was transferred into this flask, and the contents were heated under reflux for 4 hours to complete lignin precipitation. Once cooled, the

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solution was filtered through a pre-weighed crucible (No. 3), and the residue was washed thoroughly with hot distilled water to remove any remaining acid and soluble components.

The crucible containing the retained Klason lignin was oven-dried at 103 ± 2 °C for three days. Lignin content was calculated by subtracting the weight of the empty crucible from the weight of the crucible containing dried lignin. The percentage of lignin was determined using the following formula:

$$\text{Lignin content (\%)} = (Wa/Wb \times 100\%) \times ((100-ec)/100) \quad (10)$$

Where Wa is lignin weight, Wb is the oven-dried weight of extractive-free samples particles, and ec is the extractives content.

Hemicellulose content was calculated by subtracting the α-cellulose content from the holocellulose content:

$$\text{Hemicelluloses content (\%)} = \text{holocellulose} - \alpha \text{ cellulose} \quad (11)$$

3. Results and Discussion

3.1 Identification and Comparison of Anatomical Properties of *Leucaena leucocephala*

The anatomical features of *Leucaena leucocephala* fibres showed noticeable differences along the vertical stem positions, top, middle, and bottom. Table 1 presents the average values for key fibre traits, including fibre length, diameter, lumen diameter, cell wall thickness, and calculated indices such as Runkel ratio, slenderness ratio, and flexibility coefficient.

Table 1: Mean of anatomical properties and derived values of Leucaena leucocephala at different positions

Position	FL (µm)	FD µm)	FLD (µm)	FWT (µm)	RR	MR	SR	CR	FC
Top	792.5	18.5	11.5	1.4	0.17	0.61	42.84	0.08	0.62
Middle	905.0	28.0	20.5	1.5	0.11	0.46	32.32	0.05	0.73
Bottom	1072.5	22.0	15.25	1.35	0.12	0.52	48.75	0.06	0.69

FL = fiber length, FD = fiber diameter, FLD = fiber lumen diameter, FWT = fiber wall thickness
RR = Runkel ratio, MR = Muhlsteph's ratio, SR = Slenderness ratio, CR = coefficient of rigidity,
FC = flexibility coefficient

Fibre length increased from the top (792.5 µm) to the middle (905.0 µm), and was highest at the bottom (1072.5 µm). This pattern aligns with more recent findings that fibre length tends to increase from the upper to the lower parts of fast-growing plants [10]. In this study, bottom fibres were 35.3% and 18.5% longer than top and middle fibres, respectively. Longer fibres are beneficial in papermaking, as they improve strength properties such as tearing, tensile, and burst strength, as well as folding endurance [11].

Fibre diameter also varied significantly top (18.5 µm), middle (28.0 µm), and bottom (22.0 µm). Lumen diameter followed a similar trend: top (11.5 µm), middle (20.5 µm), and bottom (15.25 µm). Cell wall thickness was fairly consistent across all positions, ranging between 1.35–1.5 µm, with slightly thinner walls at the bottom. Thicker cell walls usually lead to stiffer, less flexible fibres, reducing their ability to bond effectively and weakening the resulting paper [12].

The calculated fibre indices offer further understanding of pulp suitability. The Runkel ratio, which should ideally be below 1.0 for high-quality paper, was 0.17 (top), 0.11 (middle), and 0.12 (bottom), indicating thin-walled fibres and good strength potential [13]. The slenderness ratio, which reflects fibre length relative to diameter, was highest at the bottom (48.75), suggesting moderate potential for producing strong paper, although values closer to or above 60 are generally preferred [14]. Flexibility coefficient, which indicates bonding ability between fibres, was highest in the middle (0.73), followed by the bottom (0.69) and top (0.62), supporting the idea that more flexible fibres improve paper strength due to better inter-fibre bonding [15].

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A one-way analysis of variance (ANOVA) was performed to evaluate differences in fibre characteristics of *Leucaena leucocephala* across the top, middle, and bottom portions of the stem. The results are summarised in Table 2.

Table 2: Analysis of variance (ANOVA) for fibre length, fibre diameter and fibre lumen diameter

Anatomical properties		Sum of Squares	df.	Mean Square	F.	Sig.
Fiber length	Between groups	397041.66	2	198520.83	3.48	0.04*
	Within groups	1539125.00	27	57004.63		
	Total	1936166.66	29			
Fiber diameter	Between groups	461.66	2	230.83	8.63	0.001*
	Within groups	722.50	27	26.76		
	Total	1184.16	29			
Fiber lumen diameter	Between groups	408.75	2	204.38	9.11	0.001*
	Within groups	605.63	27	22.43		
	Total	1014.38	29			

*Different superscript letters indicate significant differences at $p \leq 0.05$.

Significant variation was found in fibre length among the three portions ($p = 0.04$). Duncan's multiple range test indicated that the bottom portion (1072.5 µm) had significantly longer fibres than the top (792.5 µm), while the middle portion (905.0 µm) did not differ significantly from either. Fibre diameter also showed a highly significant difference ($p = 0.001$). The middle portion (28.0 µm) had significantly larger diameters than both the top (18.5 µm) and bottom (22.0 µm), which were statistically similar. Lumen diameter varied significantly ($p = 0.001$) across the stem. The middle portion (20.5 µm) was significantly different from both the top (11.5 µm) and bottom (15.25 µm), while the top and bottom did not differ significantly.

These findings confirm that fibre anatomical properties vary along the stem axis of *Leucaena leucocephala*. The bottom portion, characterised by longer fibres and balanced dimensions, may be more suitable for high-strength paper production due to better bonding potential and mechanical properties [14] [15].

3.2 Identification and Comparison of the Chemical Composition of *Leucaena leucocephala*

The chemical composition of *Leucaena leucocephala* varied across different stem positions (top, middle, and bottom), influencing its suitability for pulp and paper production. The analysed components included extractives, holocellulose, α-cellulose, hemicellulose, and lignin in Table 3.

Table 3: Chemical composition of Leucaena leucocephala fibres from different stem positions

Positions	Extractives (%)	Holocellulose (%)	α-cellulose (%)	Hemicellulose (%)	Lignin (%)
Top	1.99±0.34*	65.62±2.00	48.83±0.62*	16.79±1.40	29.51±4.58
Middle	1.12±0.26*	67.24±2.69	48.79±2.10*	18.44±0.62	28.96±2.84
Bottom	0.99±0.16*	68.79±1.73	52.52±0.42*	16.26±2.02	31.88±5.30

*Different superscript letters indicate significant differences at $p \leq 0.05$.

Extractives content increased from bottom to top, with the highest percentage found in the top portion (1.99%), followed by the middle (1.12%) and bottom (0.99%). Higher extractive content, often associated with bark and protective compounds, can negatively impact pulping efficiency and paper quality [16]. Thus, the bottom portion, with the lowest extractives, is more desirable for pulping.

Holocellulose content, representing the combined cellulose and hemicellulose, was highest at the bottom (68.79%), slightly lower in the middle (67.24%), and lowest at the top (65.62%). These values fall within the typical range for suitable pulp materials and suggest better fibre yield from the bottom portion [17].

α-Cellulose, the purest cellulose fraction essential for paper strength, was highest at the bottom (52.52%). Both the top (48.83%) and middle (48.79%) portions also showed satisfactory levels above 40%, indicating good pulping

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potential across all sections. Materials with α-cellulose content above 34% are generally considered viable for papermaking [18].

Hemicellulose content was relatively similar across positions, with the middle portion showing a slightly higher value (18.44%) compared to the top (16.79%) and bottom (16.26%). Hemicelluloses contribute to fibre bonding and water retention, making them important for paper formation [19]. Lignin content ranged from 28.96% to 31.88%, with the highest amount found at the bottom. While lignin provides structural support in wood, lower lignin content is preferred in pulping to reduce chemical use and improve processing efficiency [20]. The top (29.51%) and middle (28.96%) portions remained below the generally accepted threshold of 30%, indicating moderate suitability.

Statistical analysis, as summarised in Table 4, revealed significant differences in extractives and α-cellulose content among the top, middle, and bottom portions of *Leucaena leucocephala* stems.

Table 4: Analysis of variance (ANOVA) for extractives and α-cellulose

Chemical composition		Sum of Squares	df	Mean Square	F	Sig.
Extractives	Between groups	1.805	2	0.903	13.039	0.007
	Within Groups	0.415	6	0.069		
	Total	2.221	8			
α-cellulose	Between groups	27.577	2	13.789	8.360	0.018
	Within Groups	9.896	6	1.649		
	Total	37.473	8			

For extractives, the ANOVA results indicated a statistically significant difference ($p = 0.007$). Post hoc analysis using Duncan's multiple range test showed that the top portion (1.99%) had significantly higher extractives content than the middle (1.12%) and bottom (0.99%) portions. No significant difference was observed between the middle and bottom sections ($p = 0.818$). These findings suggest a higher accumulation of extractives at the upper part of the stem, which may be less favourable for pulp and paper production due to their adverse effect on pulping efficiency [21].

Similarly, α-cellulose content differed significantly between stem positions ($p = 0.018$). The bottom portion showed the highest α-cellulose content (52.52%), significantly differing from the top (48.83%) and middle (48.79%) portions, which were statistically similar ($p = 0.999$). Since α-cellulose is crucial for fibre strength and paper quality, the bottom portion appears most promising for papermaking applications [22]. These results in Table 4 confirm that chemical composition varies significantly along the stem, influencing the potential use of each section for pulp and paper purposes.

3.3 Prediction of Chemical Compositions using Fibre Length

Simple linear regression was used to evaluate the predictive relationship between fibre length and chemical composition (lignin, holocellulose, α-cellulose, and extractives) in the top, middle, and bottom portions of *Leucaena leucocephala* stems. The results are discussed below and illustrated in Fig. 1.

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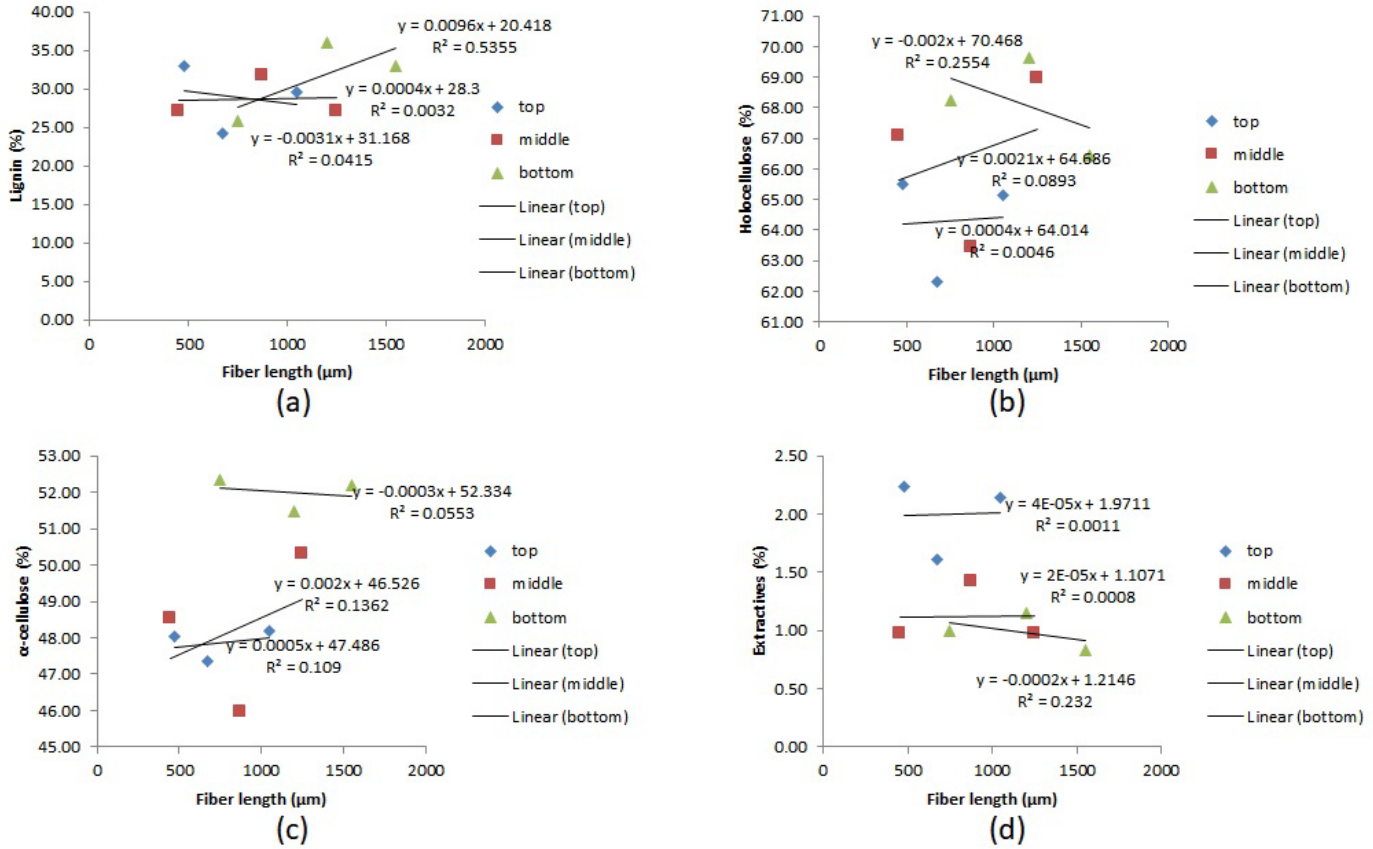

Fig. 1: Relationships between fibre length with chemical composition; (a) lignin content, (b) holocellulose content, (c) α-cellulose content, and (d) extractives content

Regression analysis showed that fibre length at the bottom portion of the stem explained 53.5% of the variation in lignin content ($R^2 = 0.535$, $t = 1.073$, $p = 0.478$), though the relationship was not statistically significant at the 0.05 level. At the top and middle portions, fibre length accounted for only 4.1% ($R^2 = 0.041$, $t = -0.208$, $p = 0.870$) and 0.3% ($R^2 = 0.003$, $t = 0.058$, $p = 0.963$) of the variation, respectively. These findings suggest that fibre length is a poor predictor of lignin content across stem positions. Similar outcomes were reported in *Acacia mangium*, where lignin biosynthesis was found to be more genetically regulated than anatomically driven [23].

The regression between fibre length and holocellulose content showed weak relationships at all stem positions. At the bottom, fiber length explained 25.6% of the variation ($R^2 = 0.256$, $t = -0.587$, $p = 0.662$), while the middle and top accounted for only 8.9% ($R^2 = 0.089$, $t = 0.313$, $p = 0.807$) and 0.5% ($R^2 = 0.005$, $t = 0.071$, $p = 0.955$), respectively. These results indicate no significant predictive power of fibre length on holocellulose content. According to Čabalová et al. [24], holocellulose levels are more closely related to physiological development stages rather than to fibre anatomical traits.

For α-cellulose, regression results showed low predictive strength across all positions. At the middle portion, fibre length explained 13.6% of the variation ($R^2 = 0.136$, $t = 0.397$, $p = 0.759$), followed by the top ($R^2 = 0.106$, $t = 0.345$, $p = 0.789$) and bottom ($R^2 = 0.057$, $t = -0.246$, $p = 0.846$). The lack of significant prediction confirms that α-cellulose accumulation is not governed by fibre elongation. This observation is consistent with the findings of [25], who noted that α-cellulose synthesis is primarily enzyme- and gene-regulated.

Regression analysis for extractives content also yielded non-significant results. Fibre length explained only 22.0% of the variation at the bottom portion ($R^2 = 0.220$, $t = -0.530$, $p = 0.690$). The top and middle showed even lower predictive values with $R^2 = 0.002$ ($t = 0.042$, $p = 0.974$) and $R^2 \approx 0.000$ ($t = 0.017$, $p = 0.989$), respectively. These results align with those of [26], who emphasised that extractives are more influenced by stress physiology and age than by anatomical parameters such as fibre length.

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4. Conclusion

The anatomical and chemical properties of *Leucaena leucocephala* wood were evaluated across different stem positions (top, middle, bottom) to assess its suitability for pulp and paper production. The bottom portion exhibited the most favourable fibre characteristics, with the longest fibre length (1072.5 μm), which is positively associated with improved paper strength properties such as tensile, tear, burst strength, and folding endurance [8]. Additionally, its lower fibre wall thickness (1.35 μm) and moderate fibre diameter (22.0 μm) suggest better fibre flexibility and bonding potential, essential for producing high-quality paper. Chemically, the bottom part also demonstrated the most desirable profile, with the lowest extractives content (0.99%), which is preferable for efficient pulping, and the highest holocellulose content (68.79%), important for pulp yield and recovery [27]. α-cellulose content across all positions was satisfactory (≥40%), indicating suitability for pulp strength development [28], while the middle portion recorded the highest hemicellulose content (18.44%), a key factor in fibre bonding and electrostatic interactions [29]. Furthermore, the middle segment had the lowest lignin content (28.96%), which is advantageous for chemical pulping due to lower delignification costs [30]. Regression analysis confirmed that fibre length was a significant predictor of major chemical components, particularly holocellulose, α-cellulose, lignin, and extractives, supporting its relevance in assessing pulp quality potential. Overall, this study provides valuable insights into the anatomical and chemical composition of *L. leucocephala*, a short-rotation species with promising applications in the paper and fibre-based industries. Future research should explore the integration of *L. leucocephala* fibres in composite and speciality pulp formulations, particularly focusing on fibre length, strength, coarseness, stiffness, and bonding potential to meet the growing demand for sustainable, high-performance bio-based materials.

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