

# Anatomical Characteristics of Unproductive *Elaeis guineensis* Stems and their Correlation with Density

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Oil palm is Indonesia's predominant estate crop, but it generates a significant amount of unproductive stem waste. This study examined the anatomical characteristics and their relationship with density from core to bark across the bottom, middle, and top sections, providing insights for effective OPS utilization. Anatomical characteristics were observed with optical and scanning electron microscopy, and the density was measured using an electronic densimeter. The vascular bundle numbers (VBN) increased from core to bark and decreased from top to bottom. The fiber bundle area (FBA) increased from core to bark and from top to bottom. The fiber length (FL), width (FW), and wall thickness (FWT) decreased from bottom to top, whereas the fiber lumen diameter (FLD) increased. The FL of all sections decreased from core to bark. The radial variation of FW, FLD, and FWT varied in each section. The fiber at the inner section of the middle section and the whole top section mostly showed third-grade pulp quality, whereas the bottom section and outer part of the middle section were mainly fourth-grade pulp quality. The density was positively correlated with VBN. FBA, FL, and FW were negatively correlated with oven-dry density, although not significantly, while FWT and FLD were not correlated with OPS density.

DOI: 10.15376/biores.19.4.9396-9415

Keywords: Anatomical characteristics; Density; Fiber properties; Unproductive oil palm stem

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## INTRODUCTION

Deforestation significantly reduces the supply of wood resources. As timber sources diminish, the need for alternative lignocellulose materials becomes increasingly urgent. Bamboo, agricultural residues (such as straw and husks), and oil palm stems are promising alternatives to timber.

The oil palm (*Elaeis guineensis* Jacq.) is the predominant estate crop in Indonesia, and its plantations have seen significant expansion in recent years. From 2018 to 2022, the plantation area grew from 14.33 million hectares to 15.3 million hectares, producing 46.8 million tons of crude palm oil. Oil palm trees have an economic lifespan of 25 to 30 years, after which they become unproductive and are usually cut down, resulting in substantial waste. Indonesian oil palm plantations annually generate 220 m<sup>3</sup>/ha of unproductive oil palm stems (OPS) (Prabuningrum *et al.* 2020; Mangurai *et al.* 2022a; b).

Utilizing the entire stem of these byproducts is essential to maximize the potential

of unproductive OPS and reduce agricultural waste. Unproductive OPS is utilized by dividing the stems into the central, inner, and peripheral zones; each section has variations in the density and vascular bundle numbers. The peripheral zone of OPS is used in furniture components (Ratnasingam and Ioras 2010), woodworking components (Balfas 2006), and composite products, such as plywood (Rosli *et al.* 2016), particleboards (Lee *et al.* 2018), and laminated boards (Prabuningrum *et al.* 2020), while the inner zone is employed in impregnated wood (Hartono *et al.* 2016) and densified impregnated woods (Mangurai *et al.* 2022a, b). So far, the central section has remained unutilized.

Understanding the characteristics of unproductive OPS is essential in evaluating their quality and potential technical applications. Specifically, the qualitative and quantitative anatomical characteristics of OPS provide valuable information for assessing their suitability for various uses. Shirley (2002) examined the anatomical characteristics of 25- and 14-year-old *Elaeis guineensis* stems and found that parenchyma cells increased toward the center, whereas vascular bundles decreased. Vascular bundle numbers increased from the bottom to the top. Oil palm fibers were irregular in length, diameter, and cell wall thickness from outer to inner zone and bottom to top level. Erwinsyah (2008) investigated the wood anatomical structures and the wood zoning determination of 27-year-old *Elaeis guineensis*. The author found that vascular bundles increased from the central point of the trunk toward the bark and showed different distributions in the three different wood zoning, namely the inner, central, and peripheral zones.

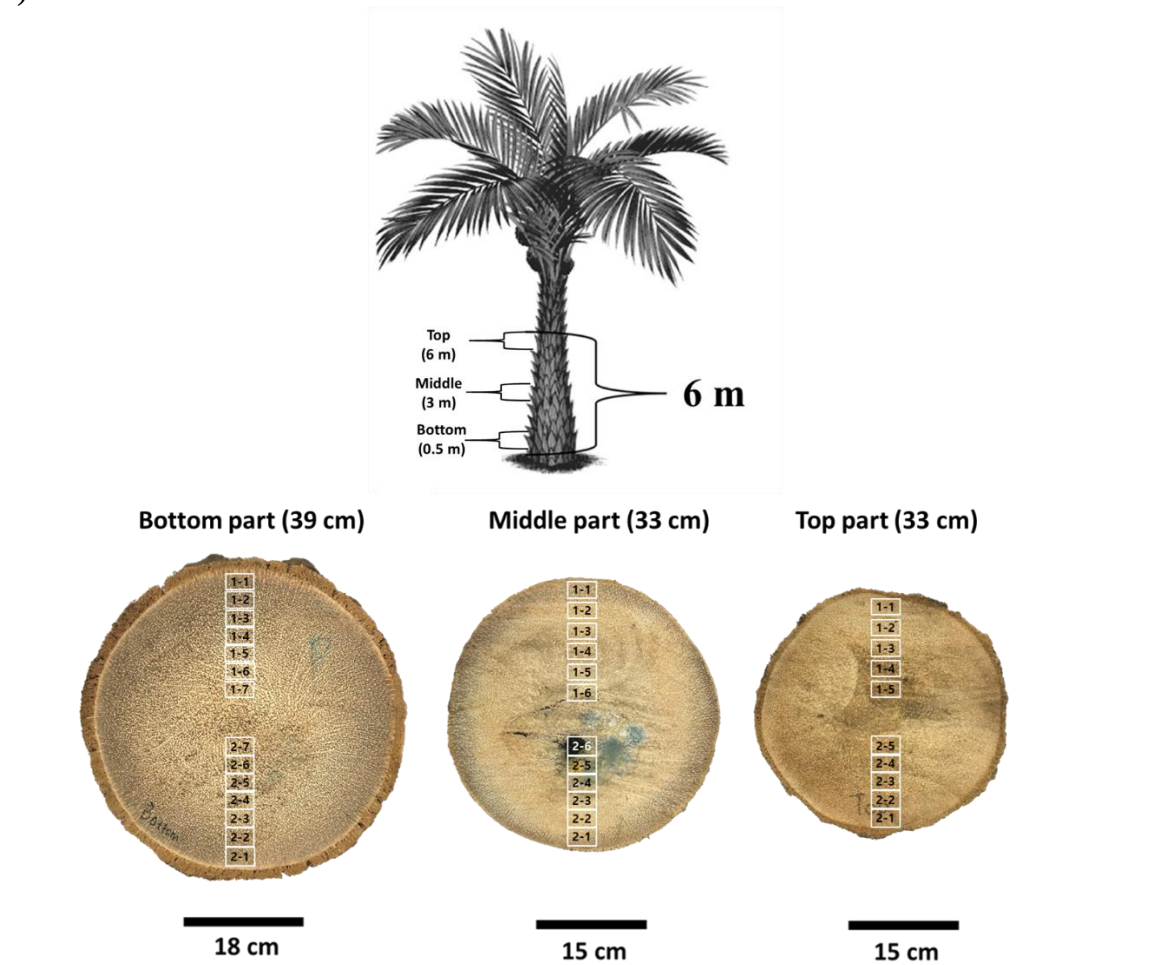
Some studies have investigated the distribution of vascular bundles and their relationship with density. Shirley (2002) reported that the density of 14- and 25-year-old OPS was highest in the outer part, which contained the highest number of vascular bundles, several layers of fiber wall, and a small number of parenchyma cells. Erwinsyah (2008) reported that the density of 27-year-old oil palm wood gradually increased from the inner zone to the peripheral zone but slightly decreased from the bottom to the top of the trunk. The influence of wood zoning in radial variation on the wood density of oil palm was higher than the trunk height. Similarly, Bakar *et al.* (2008) found that the outer part was dominated by vascular bundles, which constitute approximately 51% of the area and exhibit high density. On the other hand, the center is characterized by parenchyma tissues, which account for around 70% of the area and have low density. Darwis *et al.* (2013) found that the density of 20-year-old OPS increased from the top to bottom position and from the center to the outer part.

The potential of unproductive OPS in industries is significant. Previous studies consistently mentioned that the distribution of vascular bundles and the density were key indicators for zoning OPS, as these structures significantly influence mechanical properties such as density and strength. However, the anatomical properties of unproductive OPS, particularly within individual stems, remain poorly understood. Moreover, there is a lack of studies investigating the relationship between density and fiber properties in unproductive OPS, and little information is available on the variations in fiber quality within the stem itself. Therefore, in this study, the qualitative and quantitative anatomical characteristics of unproductive OPS in both the radial and axial directions of the stem were investigated. Additionally, the relationship between the quantitative anatomical characteristics and the density of the stem was analyzed to gain insights into the quality of unproductive OPS for effective utilization.

EXPERIMENTAL

Materials

Two trees of oil palm (*Elaeis guineensis* Jacq.) aged 35 years were harvested in 2023 from a plantation site in IPB University, Bogor, West Java, Indonesia (6°33'5.55"S, 106°42'55.35"E) (Table 1). Three wood discs were obtained from the bottom (0.5 m), middle (3 m), and top (6 m) sections of the stem, and they were oven-dried at 60 °C for 48 h. The samples were prepared every 2.5 cm from center to near bark in each section (Fig. 1).



**Fig. 1.** Bottom, middle, and top sections of OPS (above) and sample preparation at every 2.5 cm from center to near bark in each section (below)

**Table 1.** Basic Information on the OPS Samples

| Species                        | Number of trees | Age      | DBH   | Location                                                                  |
|--------------------------------|-----------------|----------|-------|---------------------------------------------------------------------------|
| <i>Elaeis guineensis</i> Jacq. | 2               | 35 years | 39 cm | IPB University, Bogor, West Java, Indonesia (6°33'5.55"S, 106°42'55.35"E) |

## Microscopy and Density Measurement

### Scanning electron microscopy

Samples with dimensions of  $10 \times 10 \times 10 \text{ mm}^3$  were softened in a 1:1 boiling mixture of glycerin and distilled water. The cross, radial, and tangential sections of the samples were trimmed with a sliding microtome (Nippon Optical Works Co, Ltd., Tokyo, Japan) and then dried in the oven at  $100 \pm 3 \text{ }^\circ\text{C}$  for 24 h. The oven-dried samples with dimensions were coated with gold using sputter coater (Cressington Sputter Coater 108; Cressington, Watford, UK). The qualitative anatomical characteristics of the OPS in the transverse, radial, and tangential surfaces were observed using a scanning electron microscope (10 kV) (JSM-5510; JEOL, Japan).

### Optical microscopy

Samples with dimensions of 10 (radial)  $\times$  10 (tangential)  $\times$  10 (longitudinal)  $\text{mm}^3$  were prepared to observe the quantitative features of vascular bundles. Vascular bundle number (VBN) was measured in 20 areas of a  $4 \text{ mm}^2$  microscopic screen in cross sections. Fiber bundle area (FBA) was measured with 50 vascular bundles. The anatomical properties were observed with a measuring microscope (MM-40; Nikon, Tokyo, Japan) connected to an image analysis system (IMT i-Solution Lite).

To observe the fiber characteristics, the samples with dimension of 1 (radial)  $\times$  1 (tangential)  $\times$  10 (longitudinal)  $\text{mm}^3$  were soaked in Schultze reagent (100 mL of 35% nitric acid [ $\text{HNO}_3$ ] and 0.6 g of 99.5% potassium chlorate [ $\text{KClO}_3$ ]) for three days and heated at 60 to  $70^\circ\text{C}$  for 1 hour (Park *et al.* 1993; Savero *et al.* 2022). The length (FL) and width (FW) of each fiber, the lumen diameter (FLD), and the single wall thickness (FWT) were measured randomly for 60 fibers using an optical microscope (Nikon Eclipse Si; Tokyo, Japan) connected to an image analysis system (IMT i-Solution Lite). The fiber derivative values were calculated from the average value of FL, FW, FLD, and FWT (Table 2). A summary of the pulp quality classification is shown in Table 3.

**Table 2.** Fiber Derivative Values and their Equations (Darwis *et al.* 2024b)

| Derivative Values of Fiber | Equation                                   |
|----------------------------|--------------------------------------------|
| Runkel ratio               | $\frac{2FWT}{FLD}$                         |
| Felting power              | $\frac{FL}{FW}$                            |
| Muhlstep ratio             | $\frac{(FD^2 - FLD^2)}{FD^2} \times 100\%$ |
| Rigidity coefficient       | $\frac{FWT}{FW}$                           |
| Flexibility ratio          | $\frac{FLD}{FW}$                           |

\*FL= fiber length; FWT = fiber wall thickness; FLD = fiber lumen diameter; FW = fiber width

**Table 3.** Pulp Quality Classification (Nurachman *et al.* 1976; Darwis *et al.* 2024b)

| Parameter                      | Class I | Class II  | Class III | Class IV |
|--------------------------------|---------|-----------|-----------|----------|
| Fiber length ( $\mu\text{m}$ ) | 2200    | 1600–2200 | 900–1600  | <900     |
| Runkel ratio                   | 0.20    | 0.2–0.5   | 0.5–1.0   | >1.0     |
| Felting power                  | 90      | 70–90     | 40–70     | <40      |
| Flexibility ratio              | 0.8     | 0.6–0.8   | 0.4–0.6   | >0.6     |
| Rigidity coefficient           | 0.1     | 0.1–0.15  | 0.15–0.2  | <0.2     |
| Muhlstep ratio                 | 30%     | 30–60%    | 60–80%    | >80%     |

### Density measurement

To measure the oven-dried density, four samples with dimension of 25 (radial) × 25 (tangential) × 25 (longitudinal) mm<sup>3</sup> were prepared from each distance level. The experiment was performed according to KS F 2198 2016 and measured with electronic densimeter (MH-330A; Omena, China).

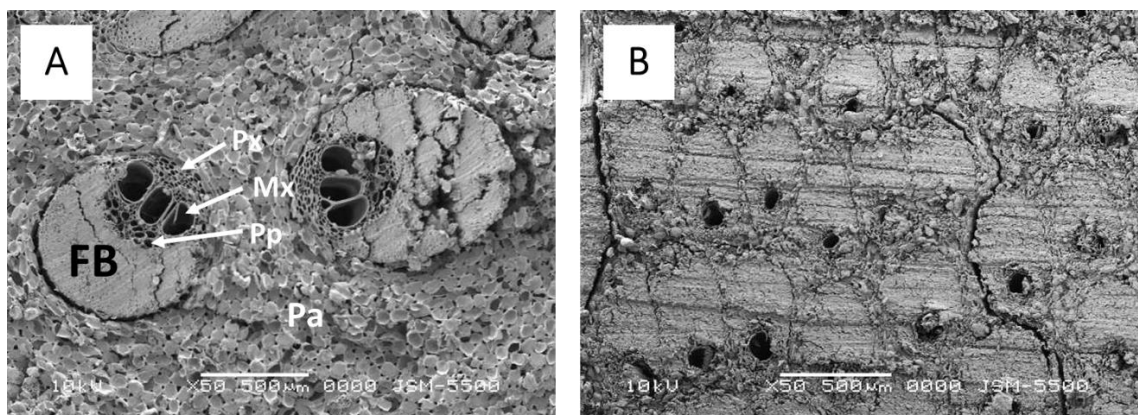
### Statistical Analyses

The quantitative anatomical characteristics in terms of the radial and axial variation of the OPS samples were analyzed for significant differences using analysis of variance (ANOVA) and post-hoc Duncan's multiple range tests. Additionally, Pearson's correlation tests were conducted to examine the correlation between each anatomical characteristic and the oven-dried density. These statistical analyses were performed using SPSS (version 24, IBM Corp., Armonk, NY, USA).

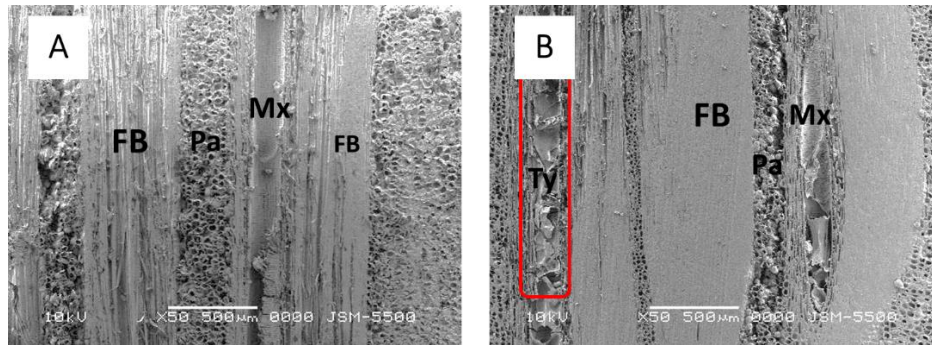
## RESULTS AND DISCUSSION

### Qualitative Anatomical Characteristics

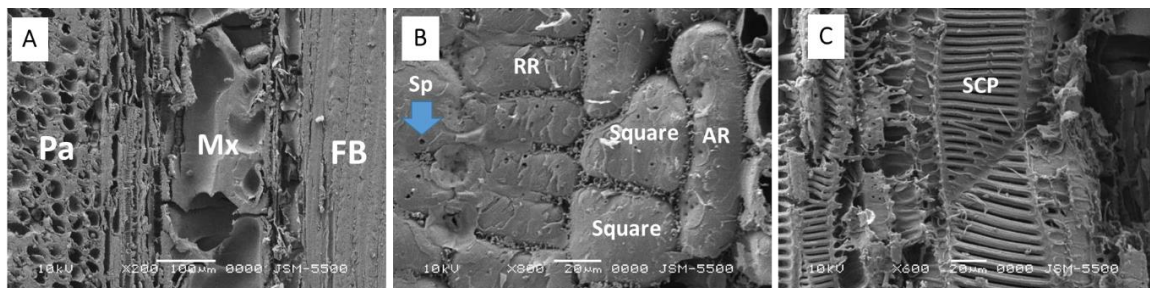
Scanning electron micrographs of the cross-section in unproductive OPS are presented in Fig. 2. The vascular bundles of *E. guineensis* consisted of fiber bundles, metaxylem, and protoxylem, and the distribution of the vascular bundle tended to be denser in the outer part (Fig. 2). In the radial and tangential section, metaxylem with tyloses and scalariform perforation plate were observed (Figs. 3 and 4), and parenchyma cells were rectangular and square shapes with simple pits (Fig. 4). The rectangular parenchyma cells were arranged in both radial and axial orientations (Fig. 4). The qualitative anatomical characteristics of the unproductive OPS in the present study aligned with the 14- and 25-year-old OPS reported by Shirley (2002). The OPS consisted of vascular bundles embedded in parenchymatous tissue. In addition, the vascular bundles generally contained vessels (metaxylem), fibrous sheaths, phloem, protoxylems, silica, and parenchyma. Furthermore, the parenchyma cells on the cross-section were isodiametric and elongated in shape. In addition, Fisher *et al.* (2002) observed a small number of tyloses or deposits in the vessels of old rattan stems, indicating that these are most likely non-functional vessels.



**Fig. 2.** Scanning electron micrographs of the cross-section in *Elaeis guineensis* trunk at 2.5 cm (A) and 17.5 cm (B) from the core. FB: fiber; Pa: parenchyma; Pp: protophloem; Mx: metaxylem or vessel; Px: protoxylem



**Fig. 3.** Scanning electron micrographs of radial (A) and tangential section (B) of *Elaeis guineensis* trunk at 17.5 cm from the core. FB: fiber; Pa: parenchyma; Mx: metaxylem or vessel; Ty: tyloses



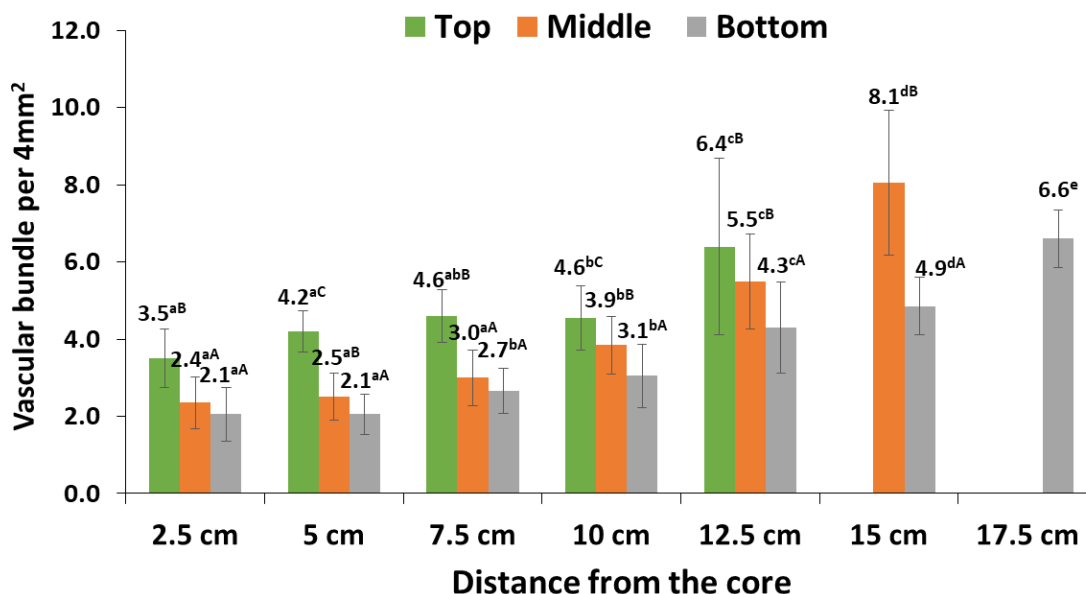
**Fig. 4.** Scanning electron micrograph of the tangential section of an *Elaeis guineensis* trunk at 17.5 cm from the core. A. Metaxylem or vessel with tyloses. B. Rectangular parenchyma cells, showing radial (RR) and axial (AR) orientations, and square parenchyma cells, all with simple pits (Sp). C. Scalariform perforation plates of a vessel (SCP)

## Quantitative Anatomical Characteristics

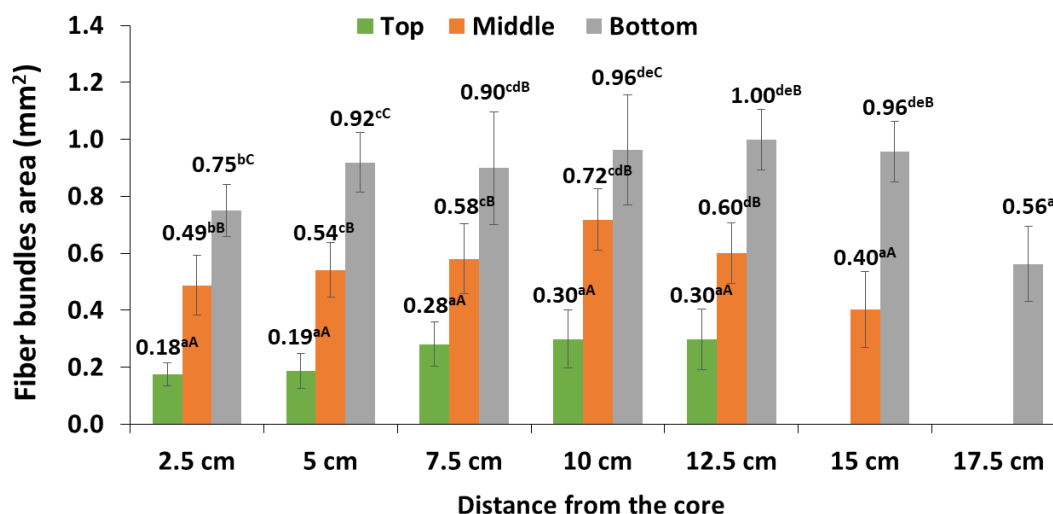
### Vascular bundle properties

VBN and FBA in the top, middle, and bottom sections of the OPS from near the core to the outer part are presented in Figs. 5 and 6, respectively. In the top, mid, and bottom sections, the VBN increased with an increasing distance from the core, whereas the top section showed a larger VBN than the bottom and middle sections. FBA significantly increased from the bottom to the top sections. The FBA increased from near the core until 12.5 cm in the bottom sections and 10 cm in the middle sections, whereas the FBA significantly decreased at the outer part. In the top section, the FBA significantly increased with increasing distance from the core.

The findings of some previous studies relating to the vascular bundle properties of younger OPS align with the present results. For example, Rahayu (2001) reported that vascular bundles cover the cross-section areas of 27-year-old OPT in the following order: 51% in the outer part, 33% in the middle section, and 30% in the center. In addition, the vascular bundles area increased from the bottom to the top. Shirley (2002) and Bakar *et al.* (2008) found that the vascular bundles of OPS were crowded at the outer part and gradually reduced in number toward the center of the stem, with a range of 42-190/cm<sup>2</sup> in a 14-year-old OPS and 51-184/cm<sup>2</sup> in a 25-year-old OPS. In addition, the VBN decreased from top to bottom level. Darwis *et al.* (2013) reported that the VBN in a 20-year-old OPS showed a low positive correlation with stem height and a high negative correlation with the distance from the outer part.



**Fig. 5.** Vascular bundle number (VBN) in the top, middle, and bottom sections of the OPS. \*The same capital letters in the same areas represent insignificant differences in axial direction, and the same lowercase letters in the same section indicate insignificant differences in radial direction.



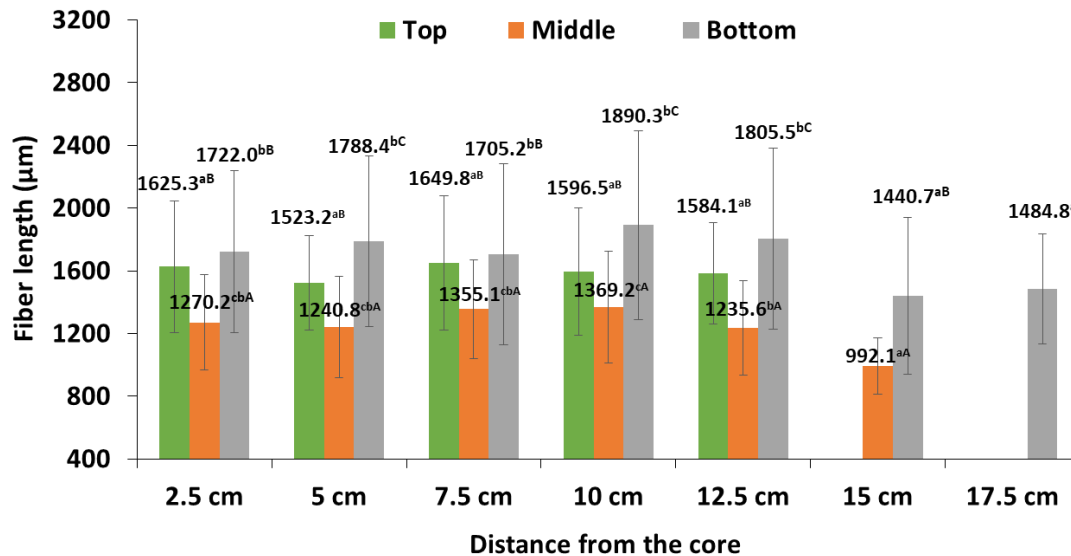
**Fig. 6.** Fiber bundle area (FBA) in the top, middle, and bottom sections of the OPS. \*The same capital letters in the same areas represent insignificant differences in axial direction, and the same lowercase letters in the same section indicate insignificant differences in radial direction.

### Fiber properties

The FL of the bottom, middle, and top section in the OPS is shown in Fig. 7. The FL was the shortest in the middle section and the longest in the bottom section. In the radial direction, the FL of the top section was constant, whereas the FL of the middle and bottom sections were significantly decreased after 12.5 cm and 15 cm from the core, respectively.

In the present study, the FL of the OPS ranged from 1485 to 1890  $\mu\text{m}$  at the bottom section, 992 to 1369  $\mu\text{m}$  at the middle section, and 1523 to 1625  $\mu\text{m}$  at the top section. Shirley (2002) and Bakar *et al.* (2008) reported that the FL in OPS decreased from the

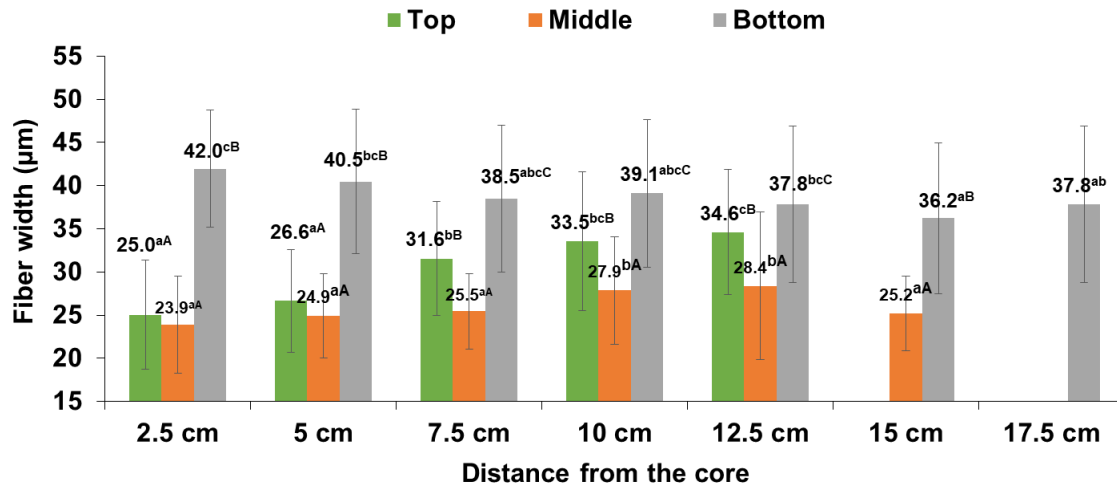
center to the outer and from the bottom to the top. The FL ranged from 1197–1864  $\mu\text{m}$  in the 14-year-old stem and 1047–1545  $\mu\text{m}$  in the 25-year-old stem. Erwinsyah (2008) reported that the fibers of a 27-year-old OPS showed closed ends and were mainly pointed, with a FL ranging from 1.9 to 2.1 mm.



**Fig. 7.** Fiber length (FL) in the top, middle, and bottom sections of the OPS. \*The same capital letters in the same areas represent insignificant differences in axial direction, and the same lowercase letters in the same section indicate insignificant differences in radial direction.

The FW of the bottom, middle, and top sections in the OPS is presented in Fig. 8. The FW of the bottom section was the largest among the sections, whereas that of the middle section showed significantly the smallest value. The top section had an intermediate FW. The FW of the bottom section gradually decreased with an increasing distance from the core, whereas that in the middle and top sections increased from the core to the bark.

In the present study, the FW of the OPS ranged from 36.2 to 42  $\mu\text{m}$  at the bottom section, 23.9 to 28.4  $\mu\text{m}$  at the middle section, and 25.0 to 34.6  $\mu\text{m}$  at the top section. Shirley (2002) reported that the outer fibers are normally smaller in diameter than the inner ones. The mean values of the FW were 35.71 to 42.47  $\mu\text{m}$  in the 14-year-old stem and 26.83 to 35.35  $\mu\text{m}$  in the 25-year-old stem. Erwinsyah (2008) reported that the average diameter of 27-year-old OPS fiber was approximately 26.1  $\mu\text{m}$ , ranging from 22 to 30  $\mu\text{m}$ , which gradually decreased from the butt end to the top of the trunk.

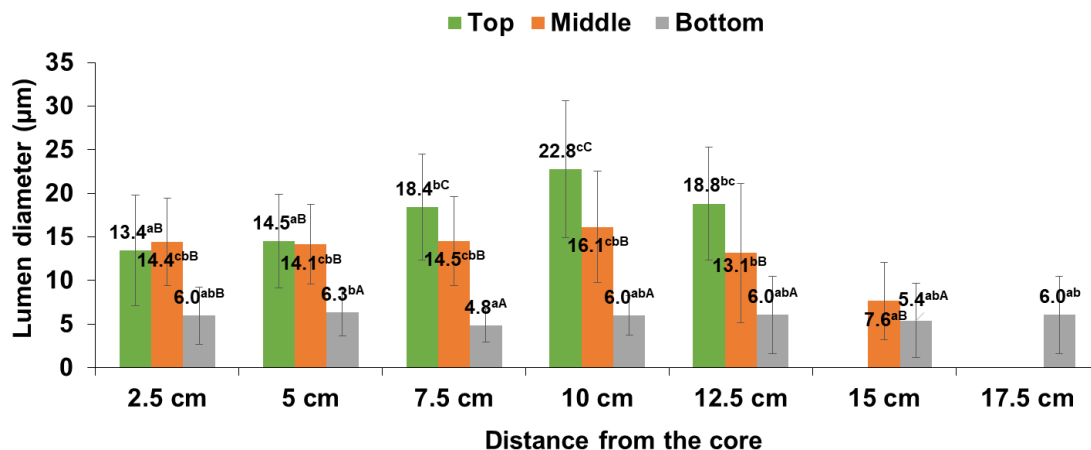


**Fig. 8.** Fiber width (FW) in the top, middle, and bottom sections of the OPS. \*The same capital letters in the same areas represent insignificant differences in axial direction, and the same lowercase letters in the same section indicate insignificant differences in radial direction.

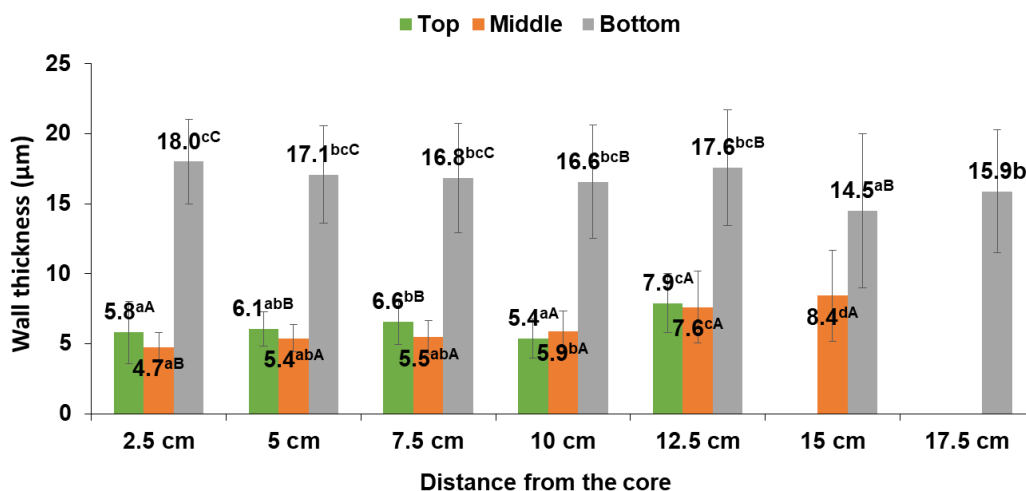
The FLD and FWT of the bottom, middle, and top sections in the OPS are presented in Figs. 9 and 10, respectively. The FLD was smallest in the bottom section of the trunk, whereas the top and middle sections showed a comparable FLD at 2.5 to 5 cm from the core. The FLD of the top section was significantly larger than that of the middle section (7.5 to 12.5 cm from the core). Regarding the radial variation, the FLD of the top section significantly increased with increasing distance from the core, whereas that of the middle section was constant until 10 cm from the core and significantly decreased at 12.5 cm. The fiber of the bottom section showed a constant FLD from the core to the bark.

The FWT at the bottom section was significantly greater than the middle and top sections, whereas the top section had a thicker cell wall than the middle section at 2.5 to 7.5 cm from the core. Both sections showed a comparable value of 10 to 12.5 cm. In the radial direction, the FWT of the bottom section was constant until 12 cm from the core and then significantly decreased. The FWT of the middle and top sections significantly decreased with increasing distance from the core.

Shirley (2002) reported that the FWT ranged from 4.70 to 6.32 µm in a 14-year-old stem and from 5.37 to 9.66 µm in a 25-year-old stem. Erwinsyah (2008) reported that the FLD of a 27-year-old OPS was 13.07 µm at a height of 2 m, 14.47 µm at 6 m, and 9.89 µm at 10 m. The FWT was 8.08 µm at a height of 2 m, 6.05 µm at 6 m, and 6.29 µm at 10 m. Abdul Khalil *et al.* (2008) reported that the FLD of OPS was 11.8 µm, while the FWT was approximately 8.0 µm.



**Fig. 9.** Lumen diameter (FLD) in the top, middle, and bottom sections of the OPS. \*The same capital letters in the same areas represent insignificant differences in axial direction, and the same lowercase letters in the same section indicate insignificant differences in radial direction.



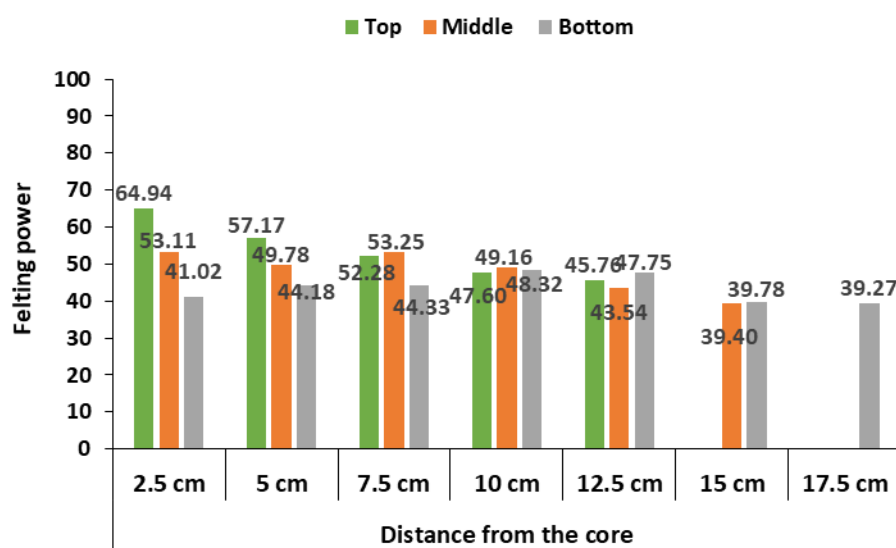
**Fig. 10.** Wall thickness (FWT) in the top, middle, and bottom sections of the OPS. \*The same capital letters in the same areas represent insignificant differences in axial direction, and the same lowercase letters in the same section indicate insignificant differences in radial direction.

#### *Fiber derivative values for pulp quality*

The felting power, flexibility coefficient, rigidity coefficient, Runkle ratio, and Muhlstroph ratio are presented in Figs. 11 to 15, respectively. The felting power of the OPS ranged from 39 to 44 in the bottom section, 39 to 53 in the middle section, and 45 to 65 in the top section. The felting power of the top section was the highest among sections at 2.5 and 5 cm from the core, whereas the bottom section had the lowest values. At 7.5 cm from the core, middle, and top sections had comparable values, while the bottom section remained the smallest. All sections showed comparable felting power from 10 cm to the bark. In the radial direction, the felting power of the top and middle sections decreased from near the core to the bark. The felting power of the bottom section increased from the core until the 12.5 cm distance and then decreased at 15 cm. The felting power of the OPS indicated third-grade pulp quality.

Felting power correlates with inter-fiber bonding, tear strength, and the tensile strength of paper sheets; the higher the felting power, the greater the strength of the paper

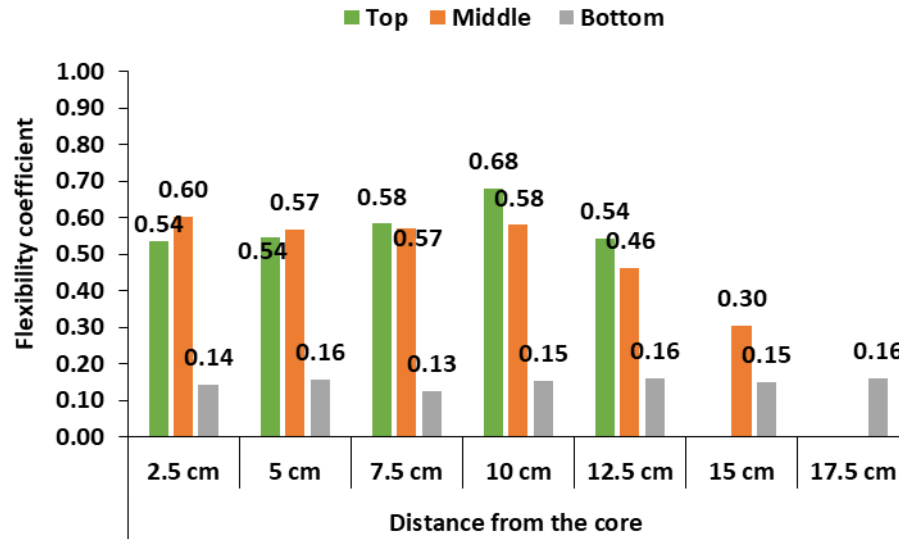
sheets (Darwis *et al.* 2024b). Abdul Khalil *et al.* (2008) reported that the felting power of OPS, empty fruit bunches, and oil palm fronds grown in Malaysia was 39.76, 37.35, and 26.13, respectively. Onuorah *et al.* (2015) found that the felting power of 35-year-old OPS grown in Nigeria was 33.44, while the empty fruit bunch was 52.88. In some fast-growing tropical species, such as *Anthocephalus cadamba* wood, the felting power ranged from 34.22 to 44.70, explicitly showing a lower value in 3-year-old *A. cadamba* than in wood aged 6 and 9 years (Darwis *et al.* 2024a). The felting power of *Styrax sumatrana* wood was 46.38 and ranged from 34.73 to 57.40, indicating third-grade pulp quality (Darwis *et al.* 2024b). The felting power in *Acacia hybrid*, *Acacia mangium*, and *Acacia auriculiformis* was 57.4, 51.29, and 52.65, respectively (Yahya *et al.* 2010). Overall, the felting power of the unproductive OPS from the core to 12.5 cm showed comparable properties to some fast-growing commercial tropical species.



**Fig. 11.** Felting power in the top, middle, and bottom sections of the OPS fibers

The flexibility coefficient of the OPS ranged from 0.1 to 0.2 at the bottom section, 0.3 to 0.6 at the middle section, and 0.5 to 0.7 at the top section. The top and middle sections had comparable flexibility coefficients at 2.5 to 7.5 cm, while the top section showed a higher value than the middle section at 10 to 12.5 cm. The bottom section had the lowest value among the sections at all distance levels. In terms of radial variation, the top and bottom sections showed a constant value from the core to the bark, whereas the middle section was constant from near the core until 10 cm and then decreased.

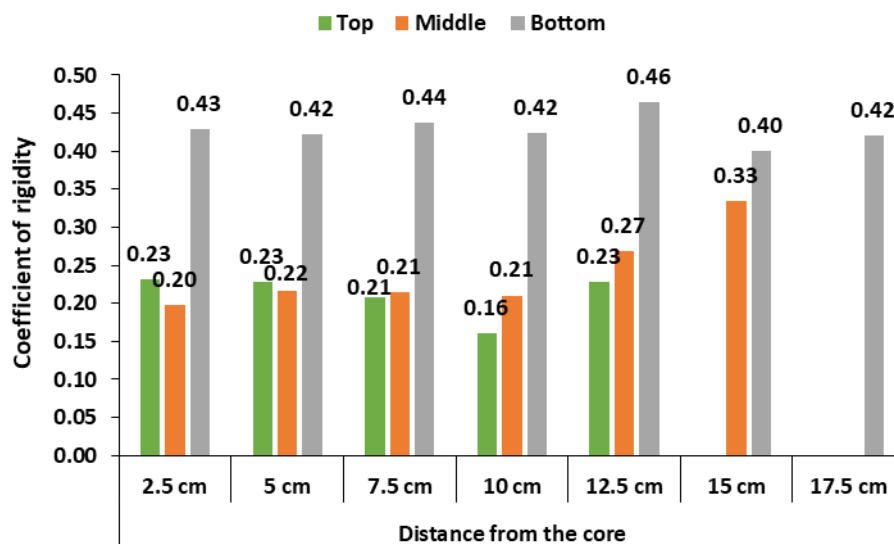
In the present study, the flexibility coefficient of the OPS in the middle (except the outer part) and top sections of OPS showed third-grade pulp quality. Furthermore, that of the bottom and the outer part of the middle sections was considered fourth-grade. The flexibility coefficient of tapped *S. sumatrana* ranged from 0.50 to 0.70, with an average of 0.61 (Darwis *et al.* 2024). The flexibility coefficient in the *A. cadamba* stem ranged from 0.55 to 0.68 (Wistara *et al.* 2015). The flexibility coefficient in *Acacia hybrid*, *A. mangium*, and *A. auriculiformis* was 0.73, 0.73, and 0.67, respectively (Yahya *et al.* 2010). Overall, the flexibility coefficient of the OPS around the core to 12.5 cm of the top and middle section showed properties comparable to some fast-growing tropical commercial species.



**Fig. 12.** Flexibility coefficient in the top, middle, and bottom sections of the OPS fibers

The rigidity coefficient of the OPS ranged from 0.40 to 0.46, 0.20 to 0.33, and 0.16 to 0.23 in the bottom, middle, and top sections, respectively. The rigidity coefficient tended to be comparable between the top and middle sections at 2.5 to 7.5 cm, while the middle section showed a larger value from 10 cm to the bark. The bottom section showed the highest value among the sections at each distance level. Regarding the radial variation, the bottom and top sections tended to be constant from near the core to the outer part. The middle section showed a decreasing rigidity coefficient from 12.5 cm to the bark.

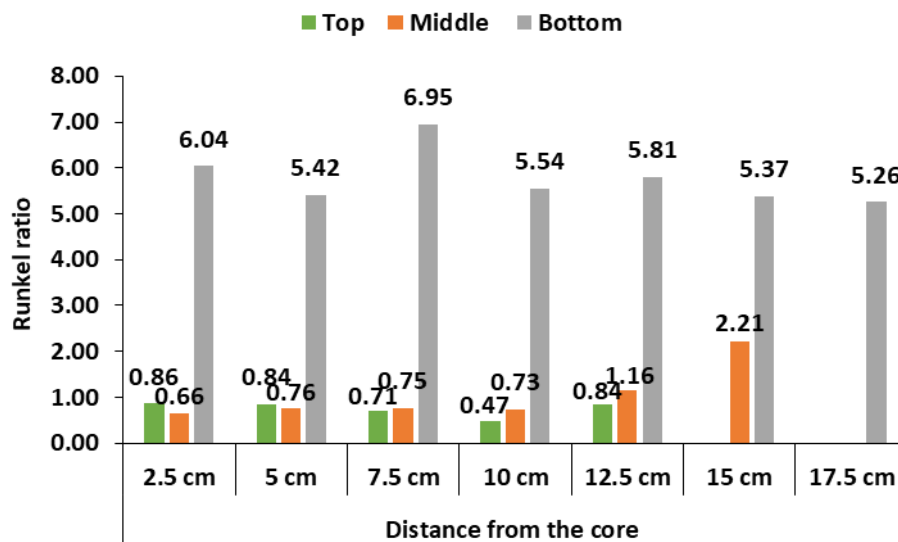
The rigidity coefficient value is the ratio of cell wall thickness to fiber diameter, reflecting the physical and chemical properties of the cell wall material as a measure of fiber conformability (Elmas *et al.* 2018). In the present study, the rigidity coefficient at the middle (except the outer part) and top section of the OPS showed third-grade pulp quality, while that at the bottom and the outer part of the middle sections was considered fourth-grade. Onuorah *et al.* (2015) reported that the rigidity coefficient of the 35-year-old OPS grown in Nigeria was 0.29, while that of the empty fruit bunch was 0.38. In some commercial tropical wood species, the rigidity coefficient of tapped *S. sumatrana* ranged from 0.50 to 0.70, with an average of 0.61 (Darwis *et al.* 2024). The rigidity coefficient in *A. cadamba* stems ranged from 0.23 to 0.42 (Wistara *et al.* 2015), while the rigidity coefficient in *A. hybrid*, *A. mangium*, and *A. auriculiformis* was 0.13, 0.13, and 0.17, respectively (Yahya *et al.* 2010). Overall, the rigidity coefficient of the OPS around the core to 12.5 cm from the core of the top and middle sections showed properties comparable to some fast-growing commercial tropical species.



**Fig. 13.** Coefficient of rigidity in the top, middle, and bottom sections of the OPS fibers

The Runkle ratio of the OPS ranged from 5.26 to 6.95, 0.66 to 2.21, and 0.47 to 0.86 in the bottom, middle, and top sections, respectively. The Runkle ratio of the bottom section showed the highest value among the sections. The Runkle ratio at 2.5 to 5 cm from the core was higher in the top section and middle section, whereas at 7.5 cm to 15 cm, the middle section had a higher value than the top section. In the bottom section, the Runkle ratio showed a decreasing trend from the core towards the outer part, whereas the value in the top section increased with increasing distance from the core. In the top section, the Runkle ratio decreased from near the core to 10 cm from the core and increased to 12 cm. The Runkle ratio in the middle (except the outer part) and top sections of the OPS showed a third-grade pulp quality, while that at the bottom and the outer part of the middle sections was considered fourth-grade.

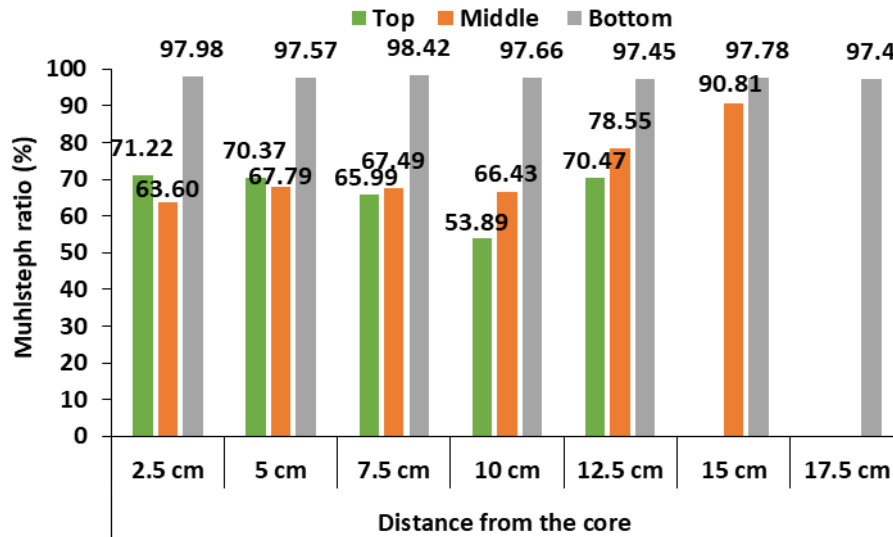
A lower Runkle ratio is preferred for high-quality fiber pulp due to its thin cell wall and wide lumen diameter, essential for achieving complete flatness and effective bonding of fiber in pulp sheets. Abdul Khalil *et al.* (2008) reported that the OPS, empty fruit bunch, and oil palm fronds grown in Malaysia showed Runkle ratios of 1.37, 0.47, and 0.57, respectively. Onuorah *et al.* (2015) reported that the Runkle ratio of the 35-year-old OPS grown in Nigeria was 0.40, while that of the empty fruit bunch was 0.62. In some commercial tropical wood species, the Runkle ratio of tapped *S. sumatrana* ranged from 0.42 to 1.00, with an average of 0.64 (Darwis *et al.* 2024b). The Runkle ratio in *A. cadamba* stems ranged from 0.23 to 0.42 (Wistara *et al.* 2015), while that in *A. hybrid*, *A. mangium*, and *A. auriculiformis* was 0.37, 0.37, and 0.55, respectively (Yahya *et al.* 2010).



**Fig. 14.** Runkel ratios in the top, middle, and bottom sections of the OPS fibers

The Muhlsteph ratio in the bottom section of OPS was approximately 98%, showing the highest value among the sections. This value remained constant from near the core to the outer part. In the middle section, the ratio ranged from 64% to 68% near the core, up to 10 cm from the core, and then increased towards the bark, reaching 79% to 91%. The ratio in this section gradually decreased from near the core until 10 cm and then increased at 12.5 cm, ranging from 54% to 71%.

The Muhlsteph ratio significantly impacts pulp sheet density, thereby influencing pulp strength. A lower Muhlsteph ratio value leads to higher-density pulp sheets with increased mechanical strength. In the present study, the middle section (except for the outer part) and the top section had a Muhlsteph ratio of 60% to 80%, indicating third-grade pulp quality. Furthermore, the Muhlsteph ratio of the bottom section and the outer part of the middle section was considered fourth-grade. Sumardi *et al.* (2020) reported that the Muhlsteph ratio of empty fruit bunches of oil palm was approximately 52%. In some commercial tropical wood species, the Muhlsteph ratio of tapped *S. sumatrana* ranged from 50.73% to 74.98%, with an average of 62.13% (Darwis *et al.* 2024b). The Muhlsteph ratio in 3- to 7-year-old *A. cadamba* stems ranged from 53% to 69% (Wistara *et al.* 2015), while the Muhlsteph ratio in *A. hybrid*, *A. mangium*, and *A. auriculiformis* was 46%, 46%, and 55%, respectively (Yahya *et al.* 2010).



**Fig. 15.** Muhlsteph ratios in the top, middle, and bottom sections of the OPS fibers

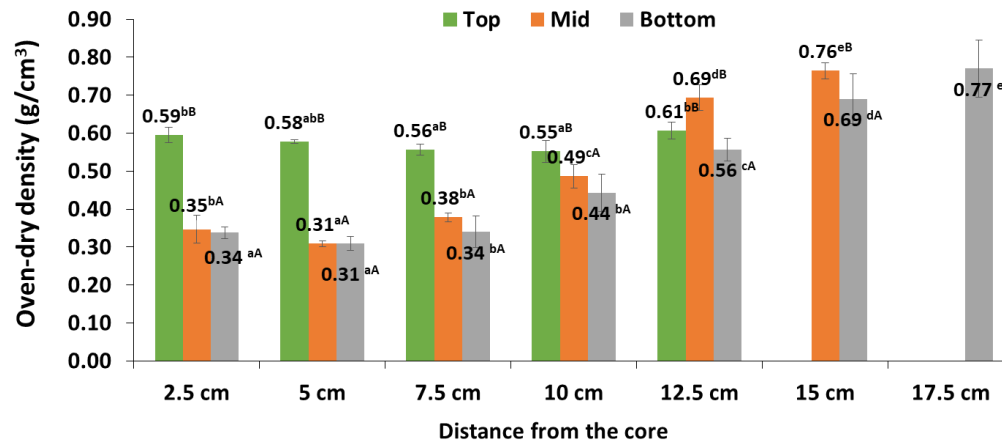
#### *Relationship between the anatomical characteristics and oven-dry density*

The oven-dry density of OPS at the top, middle, and bottom sections from near the core to the bark is shown in Fig. 16. At 2.5 to 10 cm from the core, the top section had the greatest oven-dry density among the sections, whereas the bottom section showed the smallest density. The top and middle sections had no significant difference in density at 12.5 cm from the core, whereas the bottom section was the smallest. The density of the bottom section showed a significantly lower value than the middle section at 15 cm from the core. Regarding the radial variation, the density of the top section was constant from the core to the bark. The density of the middle and bottom sections was constant from 2.5 to 7.5 cm and significantly increased at 10 cm from the core.

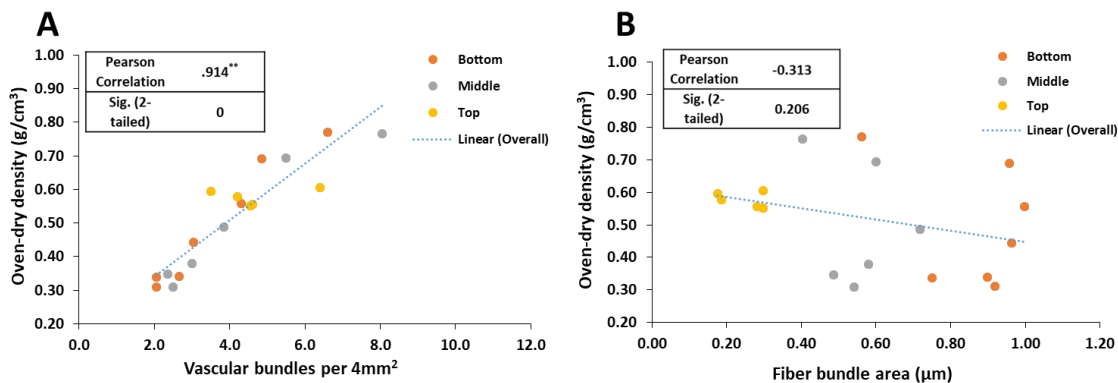
The relationship between oven-dry densities and anatomical characteristics is presented in Figs. 17 to 19. The VBN showed a significant positive correlation with oven-dry density, while the FBA, FL, and FW showed a negative correlation with oven-dry density, although not significantly. Finally, the FLD and FWT showed no correlation with the oven-dry density.

In the present study, the density in the radial and axial direction of OPS was found to be in line with the VBN, increasing from the core to the outer part and from the bottom to the top section. This observation aligns with previous research on vascular bundle density, although studies focusing on fiber properties remain scarce. Shirley (2002) reported that the density of 14- and 25-year-old OPS was highest at the outer part, which contained the highest number of vascular bundles, several layers of fiber wall, and a small number of parenchyma cells. Erwinsyah (2008) reported that the density of 27-year-old oil palm wood increased gradually from the inner zone to the peripheral zone, but decreased slightly from the bottom to the top of the trunk. The influence of wood zoning in radial variation on the wood density of oil palm was higher than the trunk height. Bakar *et al.* (2008) reported that the outer part was dominated by vascular bundles, which constitute approximately 51% of the area and exhibit high density. On the other hand, the center is characterized by parenchyma tissues, which account for around 70% of the area and have low density. Bakar *et al.* (2013) reported that the density of 32-year-old OPS at the outer part decreased linearly with stem height, whereas in the center, the middle showed the

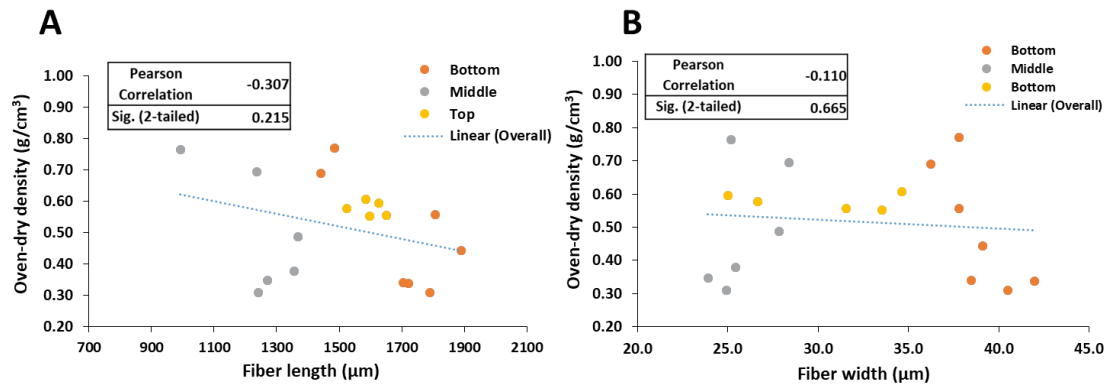
lowest density, and the bottom and top levels were similar. In addition, the density in the inner part was the highest at the top level, and the middle and bottom levels showed a comparable value. The density of the OPS decreased towards the center section from the outer part of the stems. Darwis *et al.* (2013) found that the density of 20-year-old OPS increased from the top to bottom position and from the center to the outer part. Despite some inconsistencies, a general trend of increasing density from the core to the outer zones was noted across different studies. Radial variations tended to have a more pronounced effect on OPS density compared to axial variations, showing more variability and dependence on the age and specific study methodologies.



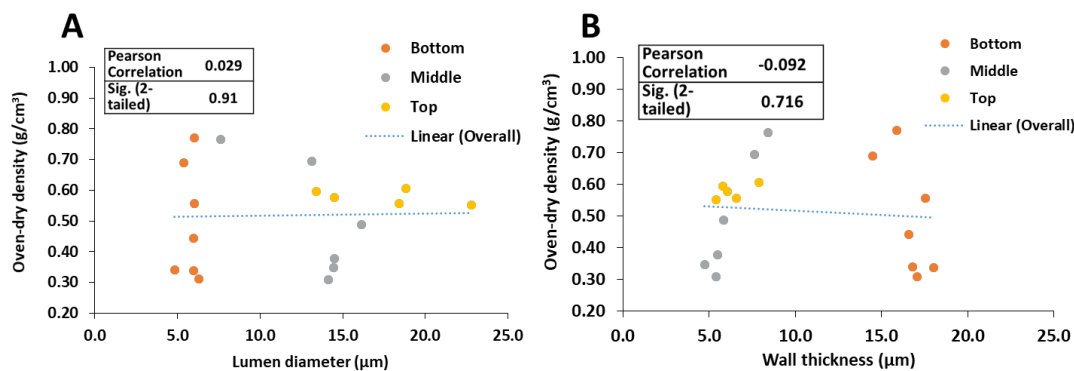
**Fig. 16.** Oven-dry density in the top, middle, and bottom sections of the OPS. \*The same capital letters in the same areas represent insignificant differences in axial direction, and the same lowercase letters in the same section indicate insignificant differences in radial direction.



**Fig. 17.** The relationship between oven-dry density with the vascular bundle number (A) and fiber bundle area (B) in OPS



**Fig. 18.** The relationship between oven-dry density with the fiber length (A) and fiber width (B) in OPS



**Fig. 19.** The relationship between oven-dry density with the fiber lumen diameter (A) and wall thickness (B) in OPS

## CONCLUSIONS

1. Unproductive OPS showed general qualitative anatomical characteristics in the three planes; however, significant differences were observed in the quantitative anatomical characteristics between the parts within the stem.
2. The VBN in all sections increased with an increasing distance from the core but decreased from the top to the bottom. FBA increased significantly from the bottom to the top sections and with an increasing distance from the core.
3. The fiber derivative values in the inner part of the middle section were comparable to those in the top section, mostly showing third-grade pulp quality, whereas the bottom section was mainly similar to the outer part of the middle section, mostly showing fourth-grade pulp quality.
4. The density increased from the core to the outer part and from the bottom to the top section, which is in line with the VBN. The FBA, FL, and FW negatively correlated with the oven-dry density, albeit not significantly, whereas the FWT and FLD did not show a correlation with the density of OPS.
5. In conclusion, there were noticeable differences in quantitative anatomical characteristics within the OPS, indicating that fiber properties could be used to

determine the quality of the stem. Overall, fiber quality decreased from the top towards the bottom section and from the core towards the outer part. In addition, future studies could explore the specific impact of these zonal variations on the mechanical performance of OPS fibers in different applications.

## ACKNOWLEDGMENTS

This research was supported by the Science and Technology Support Program through the National Research Foundation of Korea (NRF) funded by Ministry of Education (2018R1A6A1A03025582), the Ministry of Science and funded by the Ministry of Science and ICT (MSIT) (NRF-2019K1A3A9A01000018 and NRF-2022R1A2C1006470), and the Research and Development Program for Forest Science Technology (2021350C10-2323-AC03 and 2021311A00-2122-AA03) provided by the Korea Forest Service (Korea Forestry Promotion Institute).

## REFERENCES CITED

- Abdul Khalil, H. P. S., Siti Alwani, M., Ridzuan, R., Kamarudin, H. and Khairul, A. (2008). "Chemical composition, morphological characteristics, and cell wall structure of Malaysian oil palm fibers," *Polymer-Plastics Technology and Engineering* 47(3), 273-280. DOI: 10.1080/03602550701866840
- Bakar, E. S., Sahri, M. H., and H'ng, P. S. (2008). "Anatomical characteristics and utilization of oil palm wood," in: *The Formation of Wood in Tropical Forest Trees, A Challenge from the Perspective of Functional Wood Anatomy*, T. Nobuchi and M. H. Sahri (eds.), Universiti Putra Malaysia, Selangor, Malaysia, pp. 161-180.
- Balfas, J. (2006). "New approach to oil palm wood utilization for woodworking production, Part 1: Basic properties," *Indonesian Journal of Forestry Research* 3(1), 55-66. DOI: 10.20886/ijfr.2006.3.1.55-65
- Darwis, A., Karliati, T., Sutrisno, Alamsyah, E., Rumidatul, A., Melani, L., Kim, H. G., Iswanto, A. H., and Fatriasari, W. (2024a). "Chemical properties, crystallinity, and fiber biometry of Jabon (*Anthocephalus cadamba*) wood for pulp raw material: The effect of age and position," *Nordic Pulp and Paper Research Journal* 39(1), 61-71. DOI: 10.1515/npprj-2023-0053
- Darwis, A., Purusatama, B. D., Iswanto, A. H., Kim, N.-H., Hartono, R., and Susilowati, A. (2024b). "Qualitative anatomical characteristics and fiber quality of tapped *Styrax sumatrana* wood grown in North Sumatra, Indonesia," *Forests* 15(3), 509. DOI: 10.3390/f15030509
- Darwis, A., Nurrochmat, D. R., Massijaya, M. Y., Nugroho, N., Alamsyah, E. M., Bahtiar, E. T., and Safei, R. (2013). "Vascular bundle distribution effect on density and mechanical properties of oil palm trunk," *Asian Journal of Plant Science* 12(5), 208-213. DOI: 10.3923/ajps.2013
- Erwinsyah, V. (2008). *Improvement of Oil Palm Wood Properties Using Bioresin*, Ph.D. Dissertation, Technische Universitat Dresden, Dresden, Germany.
- Fisher, J. B., Tan, H. T., and Toh, L. P. (2002). "Xylem of rattans: Vessel dimensions in climbing palms," *American Journal of Botany* 89(2), 196-202. DOI: 10.3732/ajb.89.2.196

- Hartono, R., Hidayat, W., Wahyudi, I., Febrianto, F., Dwianto, W., Jang, J.-H., and Kim, N.-H. (2016). "Effect of phenol formaldehyde impregnation on the physical and mechanical properties of soft-inner part of oil palm trunk," *Journal of the Korean Wood Science and Technology* 44(6), 842-851. DOI: 10.5658/WOOD.2016.44.6.842
- KS F 2198 2016). "Determination of density and specific gravity of wood," Korean Standards Association, Seoul, Korea.
- Lee, S. H., Ashaari, Z., Ang, A. F., Halip, J. A., Lum, W. C., Dahali, R., and Halis, R. (2018). "Effects of two-step post heat-treatment in palm oil on the properties of oil palm trunk particleboard," *Industrial Crops and Products* 116, 249-258. DOI: 10.1016/j.indcrop.2018.02.050
- Mangurai, S. U. N. M., Hermawan, D., Hadi, Y. S., Sulastiningsih, I. M., Arsyad, W. O. M., Abdillah, I. B., Purusatama, B. D., Kim, J. H., Febrianto, F., Park, S. Y., and Kim, N. H. (2022a). "Resistance of the inner part of oil palm trunk impregnated with aqueous polymer-isocyanate to subterranean termite attack," *BioResources* 17(3), 5285-5299. DOI: 10.15376/biores.17.3.5285-5299
- Mangurai, S.U.N.M., Hermawan, D., Hadi, Y.S., Sulastiningsih, I.M., Basri, E., Abdillah, I.B., Maulana, M. I., Purusatama, B. D., Park, S. Y., Lee, S. H., Febrianto, F., and Kim, N. H. (2022b). "Effect of densification on the physical and mechanical properties of the inner part of oil palm trunk impregnated with methylene diphenyl diisocyanate," *Scientific Reports* 12(1), 15350. DOI: 10.1038/s41598-022-19504-x
- Nurachman, R., and Siagian, M. (1976). Dimensi Serat Jenis Kayu Indonesia; Laporan No. 75; Lembaga Penelitian: Bogor, Indonesia. (*Fiber Dimensions of Indonesian Wood Species*); Report No. 75; Research Institute: Bogor, Indonesia.
- Onuorah, E.O., Nwabanne, J.T. and Nnabuike, E.L.C. (2015). "Pulp and paper making potentials of *Elaeis guineensis* (oil palm) grown in south east, Nigeria," *World Journal of Engineering* 12(1), 1-12. DOI: 10.1260/1708-5284.12.1.1
- Park, S.-J., Lee, J.-Y., Cho, N.-S., and Cho, B.-M. (1993). *Wood Science Experiment Book*, Gwangil Munhwasa, Seoul, Korea.
- Prabuningrum, D. S. Massijaya, M. Y., Hadi, Y. S., and Abdillah, I. B. (2020). "Physical mechanical properties of laminated board made from oil palm trunk (*Elaeis guineensis* Jacq.) waste with various lamina compositions and densifications," *Journal of the Korean Wood Science and Technology* 48(2), 196-205. DOI: 10.5658/WOOD.2020.48.2.196
- Rahayu, I. S. (2001). Sifat dasar vascular bundles dan parenchyma batang kelapa sawit (*Elaeis guineensis* Jacq.) dalam kaitannya dengan sifat fisis, mekanis, serta keawetan, Master Thesis, Seola Pascasarjana IPB (Bogor). (*Basic Properties of Vascular Bundles and Parenchyma of Oil Palm (Elaeis guineensis Jacq.) Stems in Relation to Physical, Mechanical and Durability Properties*), Master Thesis, IPB Graduate School (Bogor).
- Ratnasingam, J., and Ioras, F. (2010). "Static and fatigue strength of oil palm wood used in furniture," *Journal of Applied Sciences* 10(11), 986-990. DOI: 10.3923/jas.2010.986.990
- Rosli, F., Ghazali, C. M. R., Abdullah, M. M. A. B., and Hussin, K. (2016). "A review: Characteristics of oil palm trunk (OPT) and quality improvement of palm trunk plywood by resin impregnation," *BioResources* 11(2), 5565-5580. DOI: 10.15376/biores.11.2.5565-5580
- Savero, A. M., Kim, J.-H., Purusatama, B. D., Prasetya, D., Park, S.-H., and Kim, N.-H. (2022). "A comparative study on the anatomical characteristics of *Acacia mangium* and *Acacia* hybrid grown in Vietnam," *Forests* 13(10), 1700. DOI:

10.3390/f13101700

- Shirley, M. B. (2002). *Cellular Structure of Stems and Fronds of 14 and 25 Year-Old Elaeis guineensis Jacq.*, Master Thesis, School of Graduated Study, UPM, Serdang, Malaysia.
- Sumardi, I., Hadiyane, A., Rumidatul, A., and Melani, L. (2020). “Characteristics of empty palm bunch fibers as alternative pulp material,” *American Journal of Applied Sciences* 17, 129-134. DOI:10.3844/ajassp.2020.129.134
- Wistara, N.J., Carolina, A., Pulungan, W.S., Emil, N., Lee, S.H., and Kim, N.H. (2015). “Effect of tree age and active alkali on kraft pulping of white jabon,” *Journal of Korean Wood Science and Technology* 43, 566–577. DOI: 10.5658/wood.2015.43.5.566
- Yahya, R., Sugiyama, J., Silsia, D., and Gril, J. (2010). “Some anatomical features of an *Acacia* hybrid, *Acacia mangium*, and *Acacia auriculiformis* grown in Indonesia with regard to pulp yield and paper strength,” *Journal of Tropical Forest Science* 22(3), 343–351.

Article submitted: July 30, 2024; Peer review completed: September 21, 2024; Revisions accepted: October 9, 2024; Published: October 22, 2024.  
DOI: 10.15376/biores.19.4.9396-9415