International Journal of Agriculture and Biosciences 2025 xx(x): xx-xx.
https://doi.org/10.47278/journal.ijab/2025.086

RESEARCH ARTICLE eISSN: 2306-3599; pISSN: 2305-6622

Potential Advantages of Very Short Fiber Adjacent to Small Vessel in *Acacia mangium* for Producing Paper

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ABSTRACT

"In *Acacia mangium* wood, fibers located adjacent to vessel elements are notably shorter and are referred to as 'very short fibers' to distinguish them from the longer fibers found further away from the vessels. Variations in fiber length are determined by the size of the vessel and the arrangement of the rows. The objective of our study was to determine the variation in fiber dimensions based on their distance from small vessels in the tangential direction. We also compared the quality of fibers based on their distance from small and large vessel cells as raw materials for paper production. Wood blocks measuring 10mm x 5mm x 20mm (R x T x L) were softened, sliced, and photographed using a confocal laser scanning microscope. Serial sections were aligned using Reconstruct software. Fiber length was obtained by multiplying the section thickness (25µm) by the number of cross sections in which the focused wood fibers appeared in the ImageJ software. Fiber diameter and wall thickness were measured both perpendicular and parallel to vessel enlargement. Length and lumen of the first two very short fibers adjacent to a small vessel in the tangential direction were significantly shorter and wider than those of more distant fibers. Very short fibers adjacent to small vessels in both directions had lower RR, MR, and RC values, and higher FR values, compared to distant fibers. Conversely, for very short fibers adjacent to large vessels in the radial direction only, RR, MR and RC values were higher and FR values were lower.

Keywords: *Acacia mangium*, Fiber adjacent to vessel, Reconstruct, Tangential direction, Fiber derivatives.

Article History
Article # 25-025
Received: 22-Jan-25
Revised: 10-May-25
Accepted: 24-May-25
Online First: 26-Jun-25

INTRODUCTION

In general, it is known that there are two categories of fiber length based on wood grouping, namely long and short fibers produced by softwood and hardwood species, respectively (Baker, 1995). Fiber length in softwoods ranges from 2,200µm to 3,500µm, while hardwood fiber lengths are in the range of 880µm to 1,100µm (Tripathi et al., 2018). Final paper quality is determined by the dimensions of the fibers and their derivatives (Dutt & Tyagi, 2011). The length of the fiber influences the strength, surface properties, and bonding qualities of paper produced (Anthonio & Antwi-boasiako, 2017). Fiber diameter and wall thickness affect the tear resistance of paper (Pirralho et al., 2014). Moreover, fiber wall thickness is a critical determinant of both paper strength and surface smoothness (Tofanica et al., 2011). The paper industry assesses the suitability of fiber as a raw material based on the Runkel ratio (RR), Rigidity coefficient (RC), Muhlstep ratio (MR) and flexibility ratio (FR) (Megra et al., 2022).

Acacia mangium Willd was extensively cultivated in the humid tropics of South Asia during the early 1990s. This development is relatively recent, especially when considering the extensive history of plantation forestry with non-native species like *Pinus* and *Eucalyptus*, which has been established in some countries since the late 1800s

Cite this Article as: Yahya R, Badel E, Yansen Y, Deselina D, Tampubolon JN, Damayanti R, Yunianti AD, Tazuru-Mizuno S and Zainul R, 2025. Potential advantages of very short fiber adjacent to small vessel in *Acacia mangium* for producing paper. International Journal of Agriculture and Biosciences xx(x): xx-xx. https://doi.org/10.47278/journal.ijab/2025.086

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(Wingfield et al., 2023). *A. mangium* is a hardwood species commonly used for pulp and paper production and it has been cultivated in various regions of the subtropics and tropics (Fiskari & Kilpeläinen, 2021). Between 1982 and 1985, the Research Center for Forest Tree Improvement at the Forest Science Institute of Vietnam assessed various *Acacia* species for potential commercial use and found that *A. mangium* showed the highest promise for utilization in wood industries (Savero et al., 2022). Due to the remarkable development of *A. mangium* in nations like Vietnam, Malaysia, and Indonesia, plantations of this species have rapidly expanded, feeding massive pulp mills and other timber-based industries (Wingfield et al., 2023). The primary tree species used for forest plantations in Malaysia is *A. mangium* (Jusoh et al., 2014). The species had become a cornerstone of significant forest industries. When it comes to growth and productivity, this exceptional tree faced minimal competition (Wingfield et al., 2023).

At present, *A. mangium* is among the tree species chosen for timber estate development in Indonesia. In Indonesia, forests have been created by either local communities or corporations using rapidly growing tree species, particularly *A. mangium*, Sengon (*Falcataria moluccana (Miq.),* and Eucalyptus (*Eucalyptus* spp.) (Marbun et al., 2019). The pulp and paper sector in Indonesia primarily produces pulps from mixed tropical hardwoods with shorter fiber lengths. *A. mangium* is one of the favored raw materials for the production of pulp and paper in Indonesia (Lukmandaru et al., 2020). Among the species of *Acacia*, *A. mangium* and *A. auriculiformis* are the primary species that sustain industrial plantations in Indonesia (Nirsatminto, et al., 2022).

Our previous study showed that there was variation in the length of *A. mangium* fiber (Yahya et al., 2010). Other studies have also measured variation in *A. mangium* fiber length e.g. Jusoh et al (2014) reported a fiber length of 930µm (standard error = 190µm). Our previous research further found that the length and wall thickness of a fiber varies based on its distance from the vessel and was positively associated with vessel diameter. In the radial direction, the first five fibers closest to a large vessel (diameter 171-212µm) were shorter and thicker-walled than fibers further from the vessel (Yahya et al., 2011, 2015) while the two closest fibers to a small vessel (diameter 85-109µm) were shorter (Yahya et al., 2020a) with no difference in wall thickness (Yahya et al., 2020b). In the tangential direction, the first two fibers closest to a large vessel were shorter (Yahya et al., 2011) and thicker-walled than fibers further from the vessel (Yahya et al., 2015). However, variation in length, diameter and wall thickness of fiber based on tangential distance from small vessels has not yet been studied (Fig. 1).

It has been observed that the diameter of fibers next to small vessel cells tends to be wider than those next to large vessel cells (Fig. 1). Fiber diameter is inversely proportional to felting power (FP), MR, and RC (Pirralho et al., 2014; Sangumbe et al., 2018; Marbun et al., 2019; Sadiku & Micheal, 2022) . Therefore, it is suspected that there will be differences in the FP, MR and RC values of fibers between those near to large and small vessels. The quality level of wood fibers as raw material for paper is determined by fiber length, FP, MR, RC, FR and RR (Pirralho et al., 2014; Sangumbe et al., 2018; Prasetyo et al., 2019; Nezu et al., 2021; Megra et al., 2022; NagarajaGanesh et al., 2023).

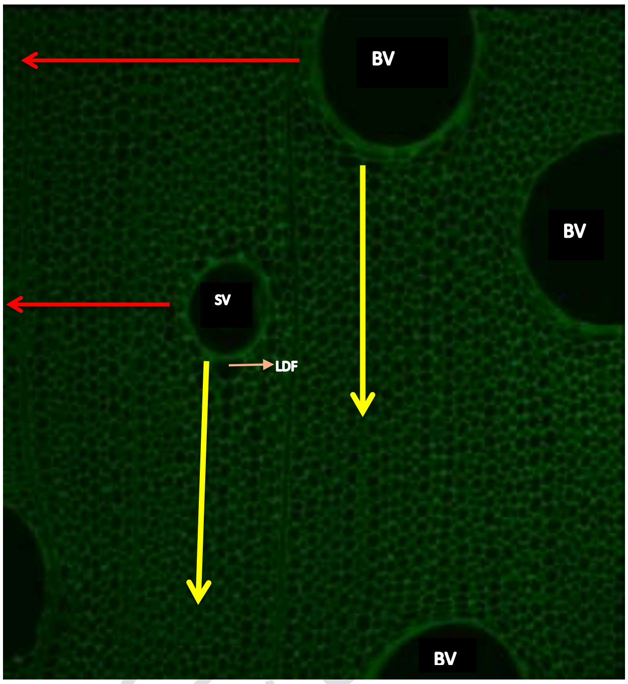

Fig. 1: *A. mangium's* transverse section demonstrates fiber cells radiating outwards from big and small vessel parallel with radial and tangential directions, indicated by yellow and red arrows, respectively. Fiber dimensions in relation to distance from small vessels in tangential direction were measured for the present study to round out measurements taken previously. BV = Big vessel; SV = Small vessel; LDF = Large diameter fiber.

With regard to the usage of fiber as a raw material for paper, all fibers whose dimensions change due to proximity to vessels can be categorized as abnormal fibers. Dimensional abnormalities of the fiber occur with the characteristics: shorter fiber (Yahya et al. 2011, 2020a), the middle of the fiber is flattened and fiber wall thickness is not balanced (Yahya et al. 2015). We feel it necessary to have a term for these abnormal fibers deformed by proximity to vessels, that distinguishes them from the general term 'short fiber' that refers to fibers produced from hardwood. We propose the term "very short fiber" for fibers adjacent to the vessel. An Illustration of the difference between very short, short and long fibers in Fig. 2.

The objective of the present study was to determine the variation in fiber dimensions based on their distance from small vessels in the tangential direction and compared the quality of fibers based on their distance (very short and distant fibers) from small and large vessel cells as raw materials for paper production.

MATERIALS & METHODS

Three dimensions (3D) reconstruction from serial cross sections requires namely three steps: slicing, photographing serial sections (Procházka et al., 2021) and computer assisted image alignment. The wood block sample (10mm × 5mm × 20mm, in radial, tangential and longitudinal directions) was prepared by cutting it from a location near the bark of a seven-year-old *A. mangium* tree in South Sumatra, Indonesia. First, the wood block was heated for 15min at 160°C; in a tiny autoclave filled with a 1:1 mixture of alcohol and glycerol to soften it (Yahya et al., 2020a). 200 slices of 25µm thick cross-sections were created by serially sectioning (Procházka et al., 2021) the softened wood block (Yahya et al., 2020b) (Fig. 3). These slices were subsequently mounted one after the other on glass slides and observed under a confocal laser scanning microscope. The series images were aligned using a free software "Reconstruct" and viewed in 3D using ImageJ software (National Institute of Health, USA) (Calì et al., 2019; Lee et al., 2020; Wu et al., 2022).

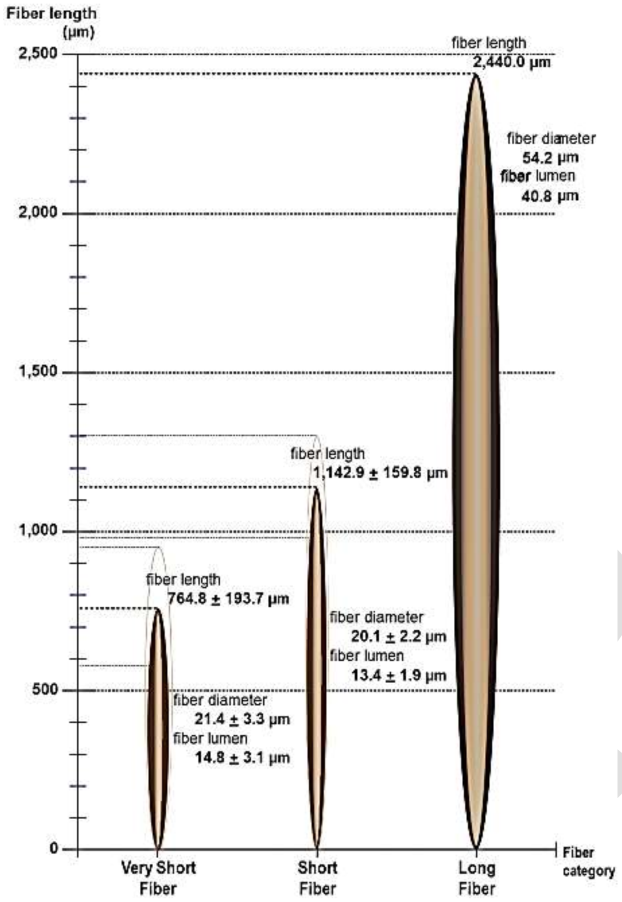

Fig. 2: Illustration of very short, short and long fiber. Average fiber dimensions for the very short and short fiber from the previous study (Yahya et al., 2011, 2020a), while for long fiber from *Pinus caribaea* Morelet reported by Oluwadare (2007).

The length and diameter of fiber cells, as well as their lumen, were measured in relation to the radial and tangential distances from large vessels (diameter 171-212µm) and small vessels (diameter 85-109µm). The number of fibers and vessel elements measured was 397 and 79, respectively. Total fiber length was calculated by multiplying the section thickness (25µm) by the total number of cross sections in which the wood fibers of interest were visible (Procházka et al., 2021). The shape of fiber cells that are away from a vessel is well described by the radial and tangential orientations in the tissue (Yahya et al., 2020b). However, fiber cells that are close to a vessel deviate from this distinct shape due to vessel expansion. We were able to calculate the cell wall thickness by measuring the fiber/lumen diameter along the relevant tangential direction of the vessel. These directions are referred as perpendicular to vessel expansion (PnVE) and direction parallel to vessel enlargement (PrVE), respectively, as the increasing vessel appears to influence the directionality of this fiber deformation. The wall thickness and diameter of fiber in the wood tissue was correlated with fiber distance from the vessel (Yahya et al., 2015).

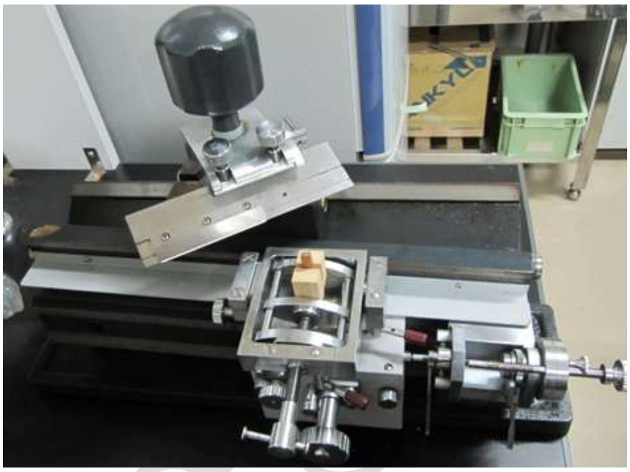

Fig. 3: Sectioning of softened wood block of *A. mangium* using a microtome.

The following formulas were used in this investigation to determine the fiber's average diameter, lumen diameter, wall thickness, and derivative values:

(1) Mean fiber diameter, FD = (radial diameter + tangential diameter) / 2
(2) Mean fiber lumen diameter, FLD = (radial diameter + tangential diameter) / 2
(3) Mean fiber wall thickness, FWT = (radial thickness + tangential thickness) / 2
(4) Fiber length (FL)
(5) Runkel ratio, RR = 2 x FWT/FLD (Villareal et al., 2022)
(6) Rigidity coefficient, RC = FWT/FD (Mari et al., 2019)
(7) Flexibility ratio, FR = FLD/FD (Villareal et al., 2022)
(8) Muhlstep ratio, MR = (FD)2 – (FLD)2/(FD)2 (Mari et al., 2019)
(9) Felting power, FP = FL/FD (Villareal et al., 2022)

Derivatives were calculated for all fibers whose parameters were most influenced by a nearby vessel. For example, the third closest fibers to a large vessel in the tangential direction showed a significantly smaller diameter compared to the four fiber outward.; However, fiber wall thickness and fiber length were only affected up to the second fiber from the vessel. Consequently, derivatives were calculated across the first third of fibers. Comparisons of length, diameter, wall thickness and lumen diameter and their derivatives for fibers near to and away from large and small vessels were evaluated using the non-parametric Mann-Whitney U and T-tests. Finally, the datasets were combined and analyzed as a whole, comparing very short and normal fibers from both large and small vessels, in both radial and tangential directions, using the Mann-Whitney U and T-tests.

RESULTS & DISCUSSION

Variability in Fiber Dimensions in Relation to Distance from Small Vessels in the Tangential Direction

Fiber length in the tangential direction increased from 685±114µm for the 1st fiber from the small vessel to 1,027±78µm for the 3rd fiber from the vessel then was relatively constant up until the 13th fiber from the vessel (Fig. 4). The data obtained is much more complete than previous research data on *A. mangium* which only reported the average fiber length of 8-year-old *A. mangium* (830.3±134.8µm) (Savero et al., 2022). The fiber length of *A. mangium* close to the pith ranged from 1,040 to 1,080µm (Nugroho et al., 2012). We presume that the majority of the fibers measured in this research were located away from the vessels. The fiber length reported in prior research was comparable to the length of the fibers positioned away from the vessel in the current study.

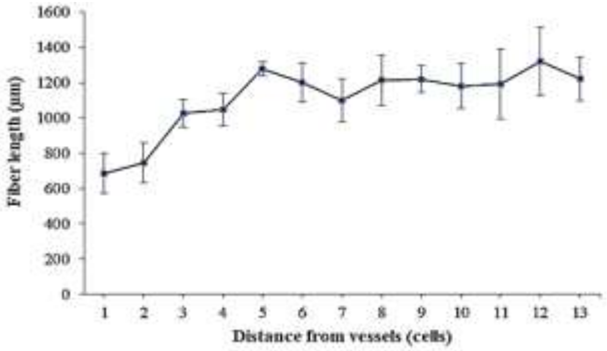

Fig. 4: Mean±SD length of fiber cells radiating outward to enlargement of the small vessel in the tangential direction.

This increase in fiber length with distance from the small vessels is similar to that previously measured of fibers radiating outwards from large vessels in the tangential direction, i.e. from 610±94 to 1,070±190µm for the 1st to 3rd fiber respectively, then relatively constant until the 10th fiber from the vessel (Yahya et al., 2011).

Mean fiber diameter PrVE was 26.4±3.2µm and 23.6±3.7µm for the 1st and 2nd fiber from the small vessel respectively, and relatively constant thereafter up to the 13th fiber (20.9±2.5µm) (Fig. 5). The fiber diameter from this current research was relatively the same as the results of previous research on 8-year-old *A. mangium*, namely 20.3±0.6µm (Sahri et al., 1993). Variation in fiber diameter in relation to small and large vessels in the tangential direction was shown in Fig. 5. For previously measured fibers near to large vessels in the same direction, average radial diameter decreased from 27.6±4.1µm to 24.6±2.5µm for the 1st and 3th fiber from the vessel, respectively. Up until the tenth fiber, the diameter of the farther-flung fibers remained largely unchanged at 21.0±3.9µm (Yahya et al., 2015).

The results indicate that the development of vessels affects the size of adjacent wood fibers during the progression from the original fusiform or xylem mother cell. Essentially, the size of the fibers is affected by the existence of the vessel (Yahya et al., 2020b). Wood fibers found adjacent to vessel elements exhibited restricted intrusive growth (Wilczek et al., 2018). As a result, the vessel would actively offer physical support to the fibers during the process of fiber enlargement, as the diameter of the fiber needs to increase in the region adjacent to where the vessel has already developed (Yahya et al., 2020b).

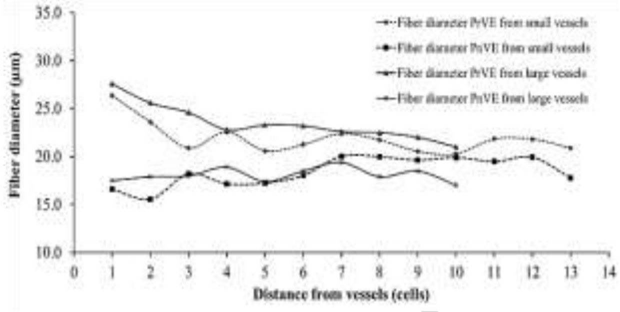

Fig. 5: Fiber diameter varies depending on the distance from small and large (Yahya et al., 2015) vessels in the tangential direction. Standard deviations are not displayed, but they range from 8% to 26% of the average value. PrVE indicates parallel to vessel enlargement, while PnVE indicates perpendicular to vessel enlargement.

The current study found no changes in fiber wall thickness with increasing distance from the small vessel in the tangential direction (Fig. 6). Previously measured fiber wall thickness adjacent to large vessels decreased from 4.2±0.7 to 4.0±0.5µm for the 1st and 2th fiber respectively, then remained relatively constant up to the 10th fiber (2.9±0.5µm) (Yahya et al., 2015) (Fig. 6). Fiber wall thickness PrVE and PnVE are 3.27 and 3.63µm, respectively. This fiber wall thickness is relatively not much different from the results of previous research on the thickness of *A. mangium* fiber wall, namely 3.67µm (Andianto et al., 2020) dan 3.76µm (Safitri et al., 2025).

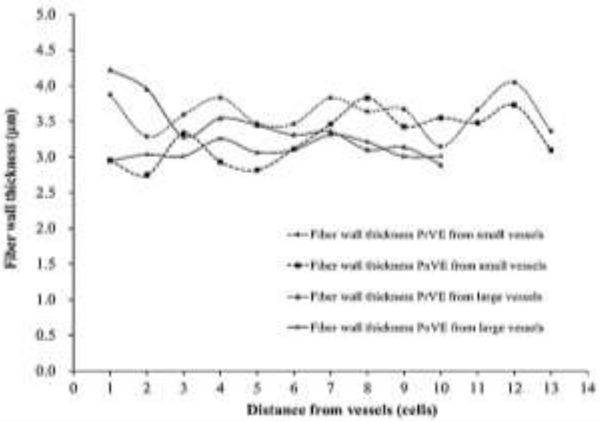

Fig. 6: Fiber wall thickness varies depending on the distance from small and large (Yahya et al., 2015) vessels in the tangential direction. Standard deviations are not displayed, but they range from 10% to 30% of the average value. PrVE indicates parallel to vessel enlargement, while PnVE indicates perpendicular to vessel enlargement.

In the tangential direction, the diameter and wall thickness of fibers near to large vessel were affected more than the diameter and wall thickness of fibers near to small vessels. This discrepancy might arise from the fact that smaller vessels put less strain on the fibers than bigger ones do, which causes the fibers next to the small vessels to deform (flatten) less severely. Fiber dimensions are determined by the events that take place during differentiation (Rao et al., 2011). The final dimensions of wood fibers are influenced by the maturation state of other surrounding xylem elements (Honjo et al., 2006). The tangential diameter of large vessels averaged 194µm, while the tangential diameter of small vessels averaged 110µm. However, this size variation did not seem to impact the number of shortened fibers nearby.

Comparison of Fiber Dimension between very Short Fiber and Fiber Distant from Vessel

In both radial and tangential rows, fibers that were far from both large and small vessels were longer than very short fibers. There was no difference in fiber wall thickness between distant fibers (from large or small vessels) and very short fibers in both radial and tangential rows (Table 1). The length of hardwood fibers determines their classification into three groups. Fibers with lengths less than 0.9mm make up the first group. The second group consists of short fibers with lengths ranging from 0.9mm to 1.933mm. Fibers with lengths exceeding 2mm are placed in the third group (NagarajaGanesh et al., 2023). The initial characteristic of fiber associated with its strength properties was fiber length (Khan et al., 2023). The length of fibers is the key indicator for assessing the appropriateness of raw materials in the pulp and paper sector, as longer fibers are more desirable (Hassan et al., 2020). Fiber length is directly proportional to burst strength, tensile strength, tear and folding endurance (Ona et al., 2001; Kiaei et al., 2014; Pirralho et al., 2014). In the fiber dimension point of view, it can be said that very short fiber has poor quality as a paper raw material compared to fibers far from large and small vessels.

Table 1: Comparisons of fiber dimensions in relation to distance from small or big vessel and direction

No	Vessel category and fiber Direction	Distance from vessel Adjacent	Distant
1	Fiber distance from big vessel in RD		
	Fiber length (µm)	730.0	1,086.0**
	Fiber diameter (µm)	19.4	19.8
	Fiber lumen (µm)	12.4	14.1*
	Fiber wall thickness (µm)	3.4	3.1
2	Fiber distance from big vessel in TD		
	Fiber length (µm)	632.0	1,096.0**
	Fiber diameter (µm)	21.7*	20.7
	Fiber lumen (µm)	15.4	14.2
	Fiber wall thickness (µm)	3.5	3.1
3	Fiber distance from small vessel in RD		
	Fiber length (µm)	875.0	1,150.0**
	Fiber diameter (µm)	25. 5**	19.8
	Fiber lumen (µm)	18.2**	13.2
	Fiber wall thickness (µm)	3.4	3.2
4	Fiber distance from small vessel in TD		
	Fiber length (µm)	700.0	1,025.0**
	Fiber diameter (µm)	21.0	19.8
	Fiber lumen (µm)	14.1*	13.1

** = significantly different at the 0.01 level; * = at the 0.05 level; RD = radial direction; TD = Tangential direction; Fiber adjacent and distant from big vessel in RD are 1- 5 fibers and 6-10 to vessel, respectively; Fiber adjacent and distant from big vessel in TD and small vessel in RD and TD are 1- 2 fibers and 3-10 to vessel, respectively.

Lumen of the two fibers closest to the small vessel in the tangential (14.1µm) and radial (18.2µm) directions were significantly wider than that of subsequent fibers (13.1µm) dan (13.2µm), respectively (Table 1 and Fig. 1). This result was in contrast to that measured of the lumen for fibers adjacent to the large vessel in the radial and tangential directions (Table 1). This result is thought to cause differences in fiber derivative values for very short fibers near to small vessels and for those near to large vessels because lumen diameter is closely correlated to paper strength (Khan et al., 2023).

Comparative Quality of very Short Fibers near to Small Vessels and those near to Large Vessels

Fibers adjacent to the large vessel in the radial direction had a larger RR, MR and RC, and smaller FP and FR than the fibers further from the vessel. In the tangential direction, the FP of fibers near to big vessels was smaller than that of fibers further away, while other derived values were not different (Table 2).

Interesting results were seen in the derivative values of very short fibers adjacent to small vessels in both radial and tangential directions. The RR of fiber adjacent to small vessel in radial (0.40) and tangential (0.42) directions were significantly lower than distant from vessel (0.47 and 0.52, respectively) (Table 2). The RR is the key and main factor utilized to assess the appropriateness of fibers for the production of paper (Hızal & Birtürk, 2024). The nearer the RR is to zero, the higher the strength and quality of the paper produced. (Jokanović et al., 2024). Fibers with a smaller RR values produce paper that is less stiff, more flexible and less bulky, with more bonding area than fibers with a greater RR (Ashori & Nourbakhsh, 2009). Fibers with a low RR positively impact tensile strength, bursting resistance, and folding durability (Ma et al., 2011).

The MR of fiber near small vessels measured in the radial (48.75) and tangential (50.54) directions was significantly lower than that measured farther from the vessels (53.92 and 56.71 respectively) (Table 2). The MR has an impact on the paper's strength, tensile, and tearing characteristics (Hızal & Birtürk, 2024). A low MR will lead to a reduced density of the pulp sheet, which in turn results in weaker pulp (Przybysz et al., 2018). The MR is inversely proportional to the bond and contact areas between the fibers (Marbun et al., 2019).

The radial (0.14) and tangential (0.15) directions of the fiber next to the small vessel showed significantly lower RC values compared to those further away from the vessel (0.16 and 0.17, respectively) (Table 2). The RC is a key factor in determining the tensile strength of paper (Wahyudi et al., 2024). The paper's tensile and bursting strengths are also negatively correlated with its RC (Marbun et al., 2019). It assesses suitability for pulp manufacture by evaluating conformability and energy requirements (NagarajaGanesh et al., 2023). The FR of fibers near small vessels in the radial (0.72) and tangential (0.70) directions was notably greater than that of fibers located farther away from the vessel (0.68 and 0.66, respectively) (Table 2). The FR is a crucial derived measure in assessing the strength characteristics of paper (Hızal & Birtürk, 2024). Fibers that possess thin walls can readily alter their shape when they have a high FR (Wahyudi et al., 2024). The FR shows how likely the fiber is to collapse while being beaten or while the paper web is drying.

Table 2: Comparison of fiber derivatives based on distance and direction to a small or big vessel

No	Distance from vessel	Runkel ratio	Felting Power	Muhlstep ratio	Flexibility ratio	Rigidity coefficient
1	Fiber distance from big vessel in RD					
	Adjacent	0.55	37.75	57.09	0.65	0.17
	Distant	0.47**	54.11**	53.01**	0.68 **	0.16**
2	Fiber distance from small vessel in RD					
	Adjacent	0.40**	37.32	48.75**	0.72**	0.14**
	Distant	0.47	59.03**	53.92	0.68	0.16
3	Fiber distance from big vessel in TD					
	Adjacent	0.46	31.65	52.83	0.69	0.16
	Distant	0.46	51.58**	52.85	0.69	0.16
4	Fiber distance from small vessel in TD					
	Adjacent	0.42*	32.71	50.54*	0.70*	0.15*
	Distant	0.52	58.59**	56.71	0.66	0.17

** = significantly different at the 0.01 level; * = at the 0.05 level; RD = radial direction; TD = Tangential direction; Fiber adjacent and distant from a big vessel in RD are 1- 5 and 6-10 fibers to the vessel, respectively; Fiber adjacent and distant from a big vessel in TD and a small vessel in RD and TD are 1- 2 and 3-10 fibers to the vessel, respectively.

The amount of collapsed fibers is directly related to the paper's strength, as they will create a larger bonding area (Ashori & Nourbakhsh., 2009). Fibers that are highly elastic and flexible can easily collapse and flatten, increasing the surface area contact, while less elastic fibers collapse partially, resulting in relative contact and fiber bonding (Riki et al., 2019).

Compared to distant fibers, very short fibers adjacent to the large vessel had lower FP (both directions) and FR values (radial direction), as well as greater RR (both directions), MR, and RC (radial direction). On the other hand, very short fibers adjacent to the small vessel in both directions had lower RR, MR, RC and FP values, and higher FR values than distant fibers (Table 2). The FP of fibers near both small and large vessels in both directions was considerably less than that of fibers located farther away from the vessels (Table 2). The FP is also referred to as the relative length of fibers or the slenderness ratio (SR) (Hassan et al., 2020). The felting power increases as the tensile strength of the paper increases (Ververis et al., 2004). A high ratio of slenderness offers defense against sheet breakage and bursting (NagarajaGanesh et al., 2023). Fiber length is more dominant in determining the value of FP. This is suspected to be the cause of the distant fibers from small vessels being larger or better as paper raw materials than adjacent fibers from vessels. All distant fibers adjacent to large and small vessels in both directions are significant longer than adjacent fibers from vessels. The length of fibers near to and far from big vessel in the radial direction were 730µm and 1,086µm, respectively, and 632µm and 1,096µm, respectively, in the tangential direction (Table 1). The length of fibers near and far from small vessels in the radial direction was 875µm and 1,150µm, respectively, and in the tangential direction was 700µm and 1,025µm, respectively (Table 1).

Based on the RR, MR, RC and FR values, very short fibers adjacent to small vessels suggest that these fibers were not necessarily inferior as raw materials for paper production, on the other hand very short fibers adjacent to large vessels, in both directions, were thus projected to be of poorer quality as paper raw materials compared to fibers located farther. The reason that these small vessel-adjacent fibers (with their low RR, MR, RC values, and high FR value) are better as paper raw materials than distant fibers is that the lumen of the adjacent fibers was significantly wider than that of distant fibers in both radial and tangential directions. This condition was not present in very short fibers that are near from large vessels. The lumen of fibers near to and far from small vessels in the radial direction were 18.2 and 13.2µm, respectively, and 14.1 and 13.1µm, respectively in the tangential direction (Table 1). Pulp beating is affected by lumen fiber. The larger the lumen diameter, the greater the beating of the pulp due to the easier penetration of liquid into the empty space of the fiber (Ververis et al., 2004; Tofanica et al., 2011; Emerhi, 2012; Khan et al., 2023).

Conclusion

Length and lumen of the first two very short fibers adjacent to a small vessel in tangential direction were significantly shorter and wider than more distant fibers. Very short fibers adjacent to small vessels in both directions had lower RR, MR, and RC values and higher FR values than distant fibers, conversely, for very short fibers adjacent to large vessels in the radial direction only, RR, MR, RC values were higher and FR values were lower. Based on the RR, MR, RC, and FR values, very short fibers adjacent to small vessels suggest that these fibers were not necessarily inferior as raw materials for paper production. On the other hand, very short fibers adjacent to large vessels were thus projected to be of poorer quality as paper raw materials compared to fibers located farther.

DECLARATIONS

Funding: This study was funded by the Directorate of Research, Technology, and Community Service, Directorate General of Higher Education, Research, and Technology, Ministry of Education, Culture, Research, and Technology of the Republic of Indonesia in 2022 (PDUPT Grant No. 105/E5/PG.02.00.PT/2022).

Acknowledgement: We would like to express our gratitude to *Séjours Scientifiques de Haut Niveau* (SSHN), the French Government, which funded the first author's trip to Clermont, France, to discuss with Dr. Eric Badel from INRAE-PIAF to improve the quality of the manuscript before submission to the International Journal of Agriculture and Biosciences.

Conflict of Interest: Authors declare no conflict of interest.

Data Availability: Data will be available at request.

Ethics Statement: Not applicable in this paper.

Author's Contribution: RY and YY conceptualized the research study, drafted the manuscript, and approved the final manuscript for publication. EB reviewed and edited the language. DD, JNT, and STM contributed to the data collection. RD, ADT, and RZ prepared the figures and tables, analyzed the results, and coordinated the experimental work.

Generative AI Statement: The authors declare that no Gen AI/DeepSeek was used in the writing/creation of this manuscript.

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