Fiber quality as measured by length and slenderness ratio of fibers adjacent to small vessels of *Acacia mangium*

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Context and objectives

Wood structure and anatomical characteristics are important considerations for pulp and paper quality (Pirralho et al 2014, Yahya et al 2017). The proportion of fiber is directly proportional to tear strength and folding endurance (Ona et al 2001). Fiber dimensions and their derivative values determine the quality of the paper produced (Dutt and Tyagi 2011). Thin-walled fibers, due to their wide lumens, will easily be bonded to other fibers, which consequently increases the strength of the paper produced (Tofanica et al 2011). Thin-walled fibers also improve the smoothness of the paper surface. The Runkel Ratio, coefficient of rigidity, Muhlstep ratio and flexibility coefficient determine the suitability of fiber for paper production (Yahya et al 2020).

Acacia shows diversity in fiber morphology. This diversity has been shown to vary between and within trees, and between provenances (Nugroho et al 2012). Diversity also occurs due to biomechanical factors among wood cells (Yahya et al 2020). The effect occurs due to cell enlargement i.e. extension or increase in cell diameter.

Vessel cells experience the greatest diameter increase in hardwoods such as *Acacia mangium* Willd. Radial diameter and wall thickness of fibers adjacent to large vessels (171–212 µm) in *A. mangium*, decreased from the first fiber to the fifth fiber, whereas the tangential diameter increased from the first fiber to the fifth fiber (Yahya et al 2015). The same tendency also occured in the length of fibers adjacent to these vessels—fiber length decreased from the first fiber to the fifth fiber, with relatively constant fiber length after that (Yahya et al 2011).

Breeding programs in Indonesia are focused on improving pulping qualities of Acacia (Nirsatmanto et al 2015) and fiber properties such as fiber length, the Runkel ratio and slenderness ratio as useful indices for plus tree selection (Ohshima et al 2011), as with vessel proportion and size assessment (Amidon 1981). For *A. mangium*, where vessels comprise 10.4% (Yahya et al 2010), fibers near small vessels (85–109 µm) had better Runkel ratios, coefficient of rigidity values and Muhlstep ratios than that of large vessels (Yahya et al 2020), indicating that trees with a higher proportion of small vessels may be desirable in breeding for pulp and paper. For the present study, our objective was to determine the length and slenderness ratio of fibers close to small in *A. mangium*, in the context of pulpwood quality evaluation.

Material and methods

A wood block of 10 mm × 5 mm × 20 mm (in radial, tangential and longitudinal directions) was cut from near the bark of a seven-year-old *A. mangium* tree. The tree was randomly selected from the trial area of a private forest plantation, Musi Hutan Persada (MHP) Company, in South

Sumatra, Indonesia. The sample was prepared following the method described in Yahya et al (2020) and given in brief below.

The wood block was first softened by autoclaving with alcohol and glycerol (1:1 ratio), serially sectioned into 200, 25 µm-thick cross-sections that were then sequentially mounted on glass slides. Photographs were taken of the sections viewed through a confocal laser scanning microscope. The software Reconstruct (Fiala 2005) was applied to align, the serial section images and ImageJ software (National Institute of Health, USA) was used to examine the aligned images in 3D.

In this study, the length and radial diameters of 178 fibers adjacent to small vessels (lumen diameter 85–109 µm) were measured. Fiber length was obtained by multiplying section thickness (25 µm) with number of cross sections in which that fiber appeared. Slenderness ratio was calculated by dividing fiber length with fiber diameter.

Mann-Whitney and t-tests were used to compare length and slenderness ratio between fiber based on their distance from small vessels (recorded in the present study) and big vessels (reported in Yahya et al 2011).

Results and discussion

Variation in fiber length

Variation in the fiber length occurred as the distance from the vessel changed. Fig. 1 shows that in the radial direction, average fiber length increased from 700 µm at the 1st fiber from the vessel to 1061 µm for the 3rd fiber from the small vessel and then was relatively constant up to the 13th fiber from the vessel. For fibers adjacent to large vessels, average fiber length increased from 610 µm at the 1st fiber from the vessel to 920 µm for the 6th fiber from the vessel and then was relatively constant (1075 µm) up to the 10th fiber from the vessel (Yahya et al 2011).

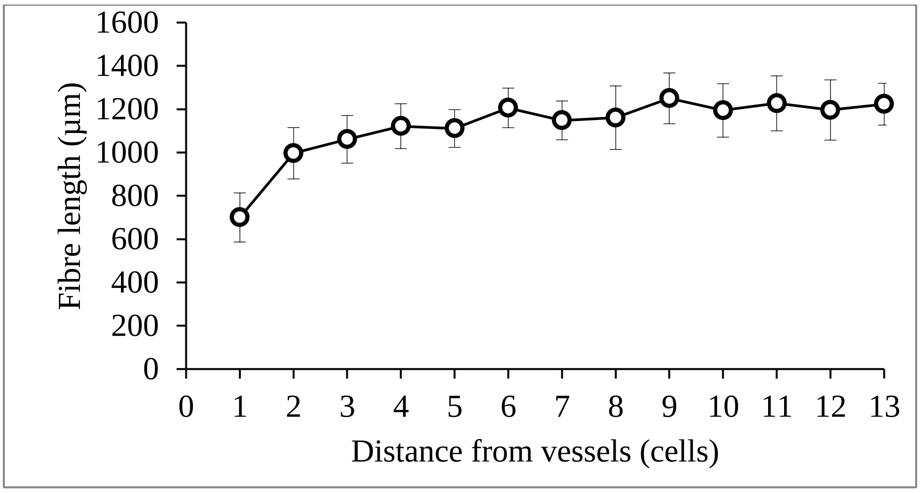

Fig. 1: Mean fiber length (± standard deviation) in relation to distance from small vessels of *Acacia mangium*

Fiber length of *A. mangium* near the pith was 1040 µm up to 1080 µm (Nurgoho et al 2012). We assume that most of the fibers measured in the study were distant from vessels. Fiber length in the previous study was relatively identical to the length of the fiber distant from the vessel in the present study.

We assume that the same fusiform initial or xylem mother cells in the cambial zone formed about two fibers in radial direction, and we hypothesize that the length of the fibers is affected by vessel maturation. The processes that occur during differentiation determine fiber dimensions (Ridoutt and Sands 1993, Rao et al 2011). The state of maturation of other nearby xylem elements affects the final dimensions of wood fibers (Honjo et al 2006).

As the results of the previous research (Yahya et al 2011), vessel-adjacent fibers decreased in length in the present study. There are differences between fibers adjacent to vessels classified as small vessels (85–109 µm) in the present study, and fibers adjacent to vessels classified as large vessels (171 –212 µm) in the previous study. Fibers close to large vessels are shortened to the fifth fiber of the vessel (Yahya et al. 2011), while those close to small vessels were only up to the second fiber.

The Mann-Whitney and t-test results in Tab. 1 show that the average length of fibers adjacent to small vessels (859 µm) was significantly greater than the length of fibers adjacent to large vessels (642 µm). But there was no statistically significant difference in fiber length between those far from large vessels (1075 µm) and small vessels (1191 µm).

Quality of fibers based on their distance from small and large vessels

Fibers adjacent to both small vessels and large vessels were significantly shorter than fibers far from those vessels (Tab. 1). No difference in length was found for fibers that were far from both small and large vessels indicating that the pressure exerted on fibers by the vessels (both small and large), only affected adjacent fibers.

Tab. 1: Mean fiber length and slenderness ratio in relation to radial distance from small and large vessels of *Acacia mangium*

1.	Distance from vessel	Fiber length (µm)	Slenderness ratio
	5 fibers to large vessel[1)]	642**	33*
	6-10 fibers from large vessel[1)]	1075	54.8
2.	2 fibers to small vessel	859**	34**
	3-13 fibers from small vessel	1191	60
3.	5 fibers to large vessel [1)]	642**	33^{ns}
	2 fibers to small vessel	859	34
4.	6-10 fibers from large vessel [1)]	1075^{ns}	54.8^{ns}
	3-13 fibers from small vessel	1191	60

** = significantly different at the 0.01 level; * = at the 0.05 level; ns = non significant
[1)] Yahya et al (2011)

These results indicate that pressure from a large vessel resulted in the shortening of five fibers, which were shorter on average than the two fibers compressed by a small vessel. The average length of the first two fibers near a small vessel was 859 µm, 28% shorter than that of the more distant fibers (1191 µm). For fibers adjacent to large vessels, which have a mean length of 642 µm, 40% shorter than that of the more distant fibers (1075 µm) (Tab. 1), indicating that the reduction in length of fibers adjacent to small vessels was smaller than the reduction in length of fibers adjacent to large vessels. Therefore, the number of shortened fibers was correlated with vessel size and the length of those shortened fibers was negatively correlated with vessel size. Wood that contains longer fibers will produce stronger paper, because fiber length is positively correlated with burst strength and tensile strength (Pirralho et al 2014), tear strength (Kiaei et al 2014) and folding endurance (Ona et al 2001).

Variation in the slenderness ratio occurred as the distance from the vessel changed. Fig. 2 shows that in the radial direction, average slenderness ratio increased from 25 at the 1st fiber from the vessel to 52 in the 3rd fiber from the small vessel and then was relatively constant up to the 13th fiber from the vessel.

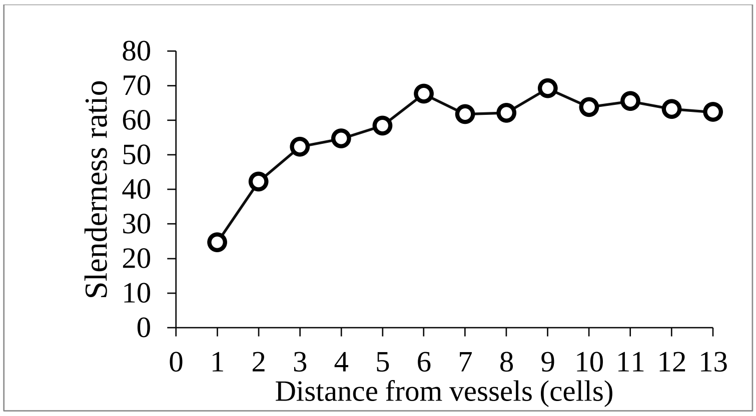

Fig. 2: Mean slenderness ratio in relation to distance from small vessels of *A. mangium*

Slenderness ratio of fibers distant from vessels in the present study was relatively the same as in the previous study. The average slenderness ratio of *A. mangium* was 54 (Jusoh et al 2014) and 51.29 (Yahya et al 2010).

The slenderness ratio of the two fibers adjacent to the small vessel was smaller than that for distant fibers, which was likewise for the five fibers adjacent to the large vessel was smaller than that for distant fibers (Tab. 1). There was no significant difference between fibers that were far from large and small vessels. Fibers adjacent to large and small vessels did not show significant differences in slenderness ratio values (Tab. 1).

Fiber length and slenderness ratio are directly proportional to the strength of the fiber (Shakhes et al 2011). Slenderness ratio determines the bonding ability of individual fibers (Omotoso and Owolabi 2015). Fibers with high slenderness ratio will greatly help fibers to collapse and inter-fiber bonding during the formation of paper. The stronger the inter-fiber bond between fibers, the higher the tensile strength, bursting strength and folding endurance of the paper produced.

The results of this research are consistent with those of our previous study that reported dimension and derivative values such as diameter, wall thickness, the Runkel Ratio, coefficient of rigidity, the Muhlstep ratio and flexibility coefficient values of fibers adjacent to small vessels were better as raw material for paper than fibers adjacent to large vessels (Yahya et al 2020). Wood that has a small diameter vessel is preferable for paper production (Takeuchi et al 2016). We thus recommend breeding *A. mangium* for smaller vessel size to produce good quality fiber as a raw material for the paper industry.

Conclusions

Small vessels only cause two adjacent fibers to be shorter compared to fibers that are distant from the vessel. The two fibers adjacent to the small vessel are significantly longer than the five fibers adjacent to the large vessel. No statistical difference was found between the lengths of the fibers that were distant from large vessels and small vessels.

There are five fibers adjacent to a large vessel that have a smaller slenderness ratio value than those distant from the vessel, but only two fibers have a smaller slenderness ratio value if they are close to a small vessel. No statistical difference was found between the slenderness ratio value of the fiber both adjacent to large and small vessels, and those far from large and small vessels.

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