Fiber quality and juvenile-mature transition evaluation of jabon (Anthocephalus cadamba) and binuang (Octomeles sumatrana)

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Abstract. Lesser-used wood species of jabon (Anthocephalus cadamba) and binuang (Octomeles sumatrana) are potential to be alternative resources to meet wood demand. Wood samples of these two species served as research materials to evaluate wood quality, mainly radial variation of fiber quality and juvenile-mature transition. Fiber quality was analyzed following Rachman and Siagian (1976). Radial variation of fiber and vessel length were used as parameters to estimate juvenile-mature transition using polynomial and segmented regression models. The results showed that jabon and binuang fiber are classified as Quality Class II and I for pulp and paper manufacturing, respectively. Juvenile-mature transition of jabon wood occurred in the segment 6 and 7, while the whole of binuang wood was still juvenile. Boundary between juvenile and mature wood on these wood species was affected by parameter and method applied.

1. Introduction

Wood supply scarcity in Indonesia's wood industries is still a severe problem. This problem has an impact on the decline performance of the forest industry sector [1], which can be seen from the decreasing volume of processed wood from 32.37 million m³ in 2012 to 15.94 million m³ in 2015 [2–5]. This problem emerges because most industries only utilize the specific high commercial wood species, especially members of Dipterocarpaceae, where the number is small compare to wood species in Indonesia’s forest. Indonesia has ±4000 potential wood species, but only less than 10% is utilized [6]. Intensive utilization of commercial woods has an impact on decreasing quantity in natural forest.

On the other hand, the forest industry sector plays a crucial role in the Indonesian economy. From 1970 to 1990, Indonesia was known as the biggest plywood producer as well as the biggest exporter. However, over the past decade, the contribution of the forest industry sector to gross domestic product (GDP) has declined from 1.03% in 2001 to 0.63% in 2013 [7]. Wood species diversification is one of the solutions to overcome the scarcity problem and to maintain the forest industry sector. Therefore, utilization of lesser-used wood species needs to be encouraged to diversify commercial wood species.

Research on the characteristics of lesser-used wood is needed to promote the species and to increase the productivity of forest resources [8]. It is necessary to provide scientific information that is useful for the proper processing and utilization of the woods. Thus, in this research, two lesser-used
wood species from tropical rainforest in East Kalimantan, Indonesia, namely jabon (Anthocephalus cadamba) and binuang (Octomeles sumatrana), were selected to be characterized. Jabon and binuang were selected because of their high availability in Indonesia’s natural forest. Based on data in ITTO [9], the availability of both species is categorized as unrestricted, which means widely available. Jabon is popular in plantation forests in Java, which is generally harvested in short rotations and small diameter. Rahayu et al. state that this species is harvested at 5-7 years [10]. Moreover, jabon and binuang are categorized as a pioneer and fast-growing species, with height and tree diameter up to 45 m and 100 cm, respectively [9,11]. Therefore, these species are potential to be commercialized.

This study is an attempt to contribute to the characteristics of two lesser-used wood species, especially in fiber quality and juvenile-mature transition. In this research, fiber quality assessment was performed to determine the possibility of the lesser-used wood species for pulp and paper production. It is conducted due to the significant increase in the Indonesian pulp and paper industry in the last two decades. It can be observed from the increasing export volume of pulp and paper, from 4.8 to 6.0 million ton during the last five years [2–5, 12]. Previous studies have proved that pulp and paper quality is strongly influenced by wood and fiber quality [13–16]. Fiber quality is affected by fiber length, fiber diameter, and fiber wall thickness. For example, the higher the percentage of longer and thinner fibers in wood raw materials, the better the quality of the fiber in producing pulp that is ideal for paper production, since longer fibers have a positive correlation with tensile strength, tear strength, and fold endurance [13,17].

In this present research, the juvenile-mature transition was also evaluated. This information is essential as practical information for industries for appropriate processing and utilization [10]. It is generally known that the existence of juvenile wood will cause some problems in wood processing and utilization, since juvenile and mature wood have different characteristics [18–19]. Compared to mature wood, juvenile wood is characterized by shorter fiber, thinner cell wall, lower density, greater microfibril angle, lower modulus of elasticity, higher lignin, lower cellulose, and lower extractive content [19–22]. Furthermore, wood products made from juvenile wood have different performance characteristics compared to mature wood, for example, lathe check veneer from juvenile wood is larger than mature wood [23]; physical, mechanical, and chemical properties of thermally modified juvenile wood is different compared to mature wood [24–26]; volumetric shrinkage of juvenile wood is higher than mature wood [18]; as well as pulp yield and pulp properties from juvenile wood are different compared to mature wood [25,27]. Hence, it is necessary to have an accurate wood’s juvenile-mature transition, so that industries can separate juvenile and mature wood to minimize the negative influence on end products. Moreover, the juvenile-mature transition information can be used by silviculturists for plantation forest manipulation, for example, by using a small spacing over the first years to minimize the formation of juvenile wood.

Several parameters can be used to estimate the juvenile-mature transition such as fiber length, mechanical properties, microfibril angles (MFA), and latewood percentage [22]. The most common parameter used is fiber length [10,22,28–30]. Determination of juvenility on softwood has been widely studied and generally used the tracheid characteristic, since it is the largest component of softwood, whereas tracheid length will be longer than fusiform cell [28]. Compared to softwood, hardwood has different characteristics. The conducting and supporting functions of softwood are performed by tracheid. In hardwood, these functions are divided into two different types of cells, namely fiber and vessel. The vessels proportion in hardwood is relatively high at 20-60% [31]. It is the reason for the researcher to use vessel length as one of the indicators to determine the juvenility.

The simplest way to estimate juvenile-mature transition is by visual observation on the radial variation in wood properties [32–33]. The mature zone can be inferred formed when the parameters are constant. However, this method gives indefinite value due to the presence of transition zones in wood. The other method that gives a more definite value for juvenile-mature transition is the segmented regression model. This model is one of the most common models that used to estimate juvenile-mature transition [10,23,34]. However, segmented regression model has a statistical problem because this model ignores the interdependencies of wood properties from adjacent annual rings [33].
The polynomial model has been used to overcome the limitation [35–36]. Thus, in this current research, estimation the juvenile-mature transition was done by segmented regression model and polynomial regression. Therefore, the main objective of this present study was to analyse the fiber quality and to determine the juvenile-mature transition of jabon and binuang wood.

2. Materials and methods

2.1. Sample preparation

Wood samples were collected from tropical rain forest concession area in East Kalimantan Province, Indonesia. A disk with 5 cm thickness for each jabon and binuang wood with ± 40 cm in DBH (diameter at breast height) was obtained from basal area of the stem. From each disk, a radial strip was extracted and divided into 9 segments with the same size (2 cm × 2 cm × 2 cm); that is used for specific gravity (SG) measurement and for maceration (Figure 1). Segmentation is performed at a distance of 1–1.5 cm from pith and bark, as shown on Figure 1. Assessment of radial variation was conducted on only half part of the disk. It was assumed that the wood was free from reaction wood, so the radial features of this half disk represented the other one. SG data on the radial variation was obtained according to BS 373:1957 [37]. SG and maceration samples were used for determination of fiber quality and juvenile-mature transition (Figure 1).

![Figure 1. Schematic of sample preparation.](image)

2.2. Measurement of fiber dimension and its derived values

Fiber dimension was measured by macerated specimens that were prepared by modified Franklin’s method in Rulliaty [38]. Match stick-sized samples were made, then 30% hydrogen peroxide and 60% acetic glacial mixture (1:1 by volume) were used to macerate it. The macerated materials were washed for acid-free and then were stained with safranin.

\[
FP = \frac{L}{d} \quad (1)
\]

\[
FR = \frac{l}{d} \quad (2)
\]

\[
CR = \frac{w}{d} \quad (3)
\]

\[
\% MR = \left(\frac{d^2 - l^2}{d^2}\right) \times 100 \quad (4)
\]

\[
RR = \frac{2w}{l} \quad (5)
\]

Fifty individual fibers for each segment were measured using a light microscope equipped with a photographic device (Zeiss Axio Imager A1m) to obtain the mean data of fiber length (L), fiber wall
thickness (w), lumen diameter (l), and fiber diameter (d). Furthermore, the derived values of fiber dimension namely runkle ratio (RR), felting power (FP), Muhlsteph ratio (MR), coefficient of rigidity (CR), and flexibility ratio (FR) were also calculated. These values were used to evaluate fiber quality for pulp and paper manufacturing. Formulas for the derived value of fiber dimension were as followed:

The fiber quality in this current research are classified based on the criteria of Rachman and Siagian [39] as shown in Table 1.

**Table 1.** Criteria fiber quality for pulp and paper manufacturing by Rachman and Siagian [39].

| Criteria   | Class I       | Class II      | Class III     |
|------------|---------------|---------------|---------------|
|            | Requirement   | Value         | Requirement   | Value         | Requirement | Value |
| L (µm)     | >2000         | 100           | 1000–2000     | 50            | <1000       | 25    |
| FP         | >90           | 100           | 50–90         | 50            | <50         | 25    |
| MR         | <30           | 100           | 30–60         | 50            | 60–80       | 25    |
| FR         | >0,80         | 100           | 0,50–0,80     | 50            | <0,50       | 25    |
| RR         | <0,25         | 100           | 0,25–0,50     | 50            | 0,50–1,0    | 25    |
| CR         | <0,10         | 100           | 0,10–0,15     | 50            | >0,15       | 25    |

| Scoring    | 450–600       | 225–449       | <225          |

*aL:fiber length; FP:felting power; MR:Muhlsteph ratio; FR:flexibility ratio; RR:Runkle ratio; coefficient of rigidity.

2.3. Estimation juvenile-mature transition

Estimation the juvenile-mature transition was determined by polynomial and segmented regression model. Radial variation of fiber and vessel length were used as the parameters. It was assumed that fiber and vessel length will increase rapidly until a certain point and then become constant or the changing becomes relatively small. The constant zone indicates the mature wood zone.

For the first model, radial variation of fiber and vessel length were plotted by polynomial regression to obtain a graph, then juvenile-mature transition was determined visually by observing where the parameters reached constant values. For the second model, a segmented regression model were used. It is assumed that radial variation of fiber and vessel length can be described by two functions, i.e., steep slope and constant slope. Steep slope described juvenile wood, while constant slope described mature wood. The function of fiber/vessel length and segmentation used was:

\[ Y = a + bX + cX^2 + E \]  

(6)

Where: \( Y \) = independent variable (fiber and vessel length), \( X \) = segmented from pith to bark, \( a \) = intercept of the line of the juvenile wood, \( b \) and \( c \) = regression coefficients, and \( E \) = error.

Theoretically, it can be stated that if \( X<X_o \), it will be a quadratic equation (steep slope), whereas if \( X \geq X_o \), it will be constant [10]. Regression model for this function can be illustrated as in Figure 2. Determination of the boundary can be directly obtained using PROC NLIN in SAS 9.1.
3. Results and discussion

3.1. Fiber and vessel dimensions
Fiber dimensions are important parameters for determining fiber quality in the pulp and paper production, while fiber and vessel dimensions can be used to evaluate the boundary of juvenility. The mean values of fiber length, fiber diameter, lumen diameter, fiber wall thickness, vessel length, and vessel diameter of jabon and binuang are presented in Table 2.

| Parameter | Fiber length | Fiber diameter | Lumen Diameter | Fiber wall thickness | Vessel length | Vessel diameter |
|-----------|--------------|----------------|----------------|----------------------|---------------|----------------|
| A. cadamba | 1671.21      | 38.94          | 30.64          | 4.15                 | 953.85        | 274.39         |
| O. sumatrana | 1763.80     | 38.47          | 33.32          | 2.57                 | 511.14        | 272.70         |

Fiber length of jabon ranged from 1,330.72–1,843.31 µm for an average of 1,671.21 µm, while binuang ranged from 1,328.17–2,122.78 µm for an average of 1,763.80 µm. Fiber wall thickness jabon ranged from 2.98–5.42 µm for an average of 4.15 µm, while binuang ranged from 1.90–3.63 µm for an average of 2.57 µm. The average fiber length of these two species is greater than the value reported by Aprianis and Rahmayanti [40] and Marbun et al. [41], whereas benuang’s average fiber wood thickness in the present study is lower than that reported by Marbun et al. [40–41]. The fiber length and fiber wall thickness of jabon reported by Aprianis and Rahmayanti [40] were 1,561 µm and 2.79 µm respectively, while the benuang wood was 1,427 µm and 1.98 µm; although the report did not clarify the tree diameter and the sample position (the distance from the pith). Marbun et al. [41] reported benuang fiber length and fiber wall thickness as 1,565.60 µm and 3.06 µm respectively.

3.2. Fiber quality
Analysis of fiber quality was conducted based on Rachman and Siagian [39]. It showed that wood fiber of jabon was classified in Quality Class II (Table 3). The results also showed that fibers length values tend to increase from pith to bark. The shorter fibers near pith indicated the presence of juvenile wood.

The presence of juvenile wood is undesirable in wood processing, including in pulp and paper production [22]. Pulp yield from juvenile wood was lower than mature wood either based on the dry or wet weight [25,42]. Furthermore, the tear and opacity paper from juvenile wood were lower than
mature wood. Nevertheless, the juvenile wood fiber has high tensile strength because it has a thinner fiber wall than mature wood fiber. These thin-walled fibers contribute to the flexibility of these fibers.

Table 3. Fiber quality of jabon.a

| Criteria | 1       | 2       | 3       | 4       | 5       | 6       | 7       | 8       | Mean  |
|----------|---------|---------|---------|---------|---------|---------|---------|---------|-------|
| L (µm)   | 1330.72 | 1461.75 | 1576.48 | 1649.71 | 1843.31 | 1770.58 | 1830.67 | 1769.02 | 1808.59 | 1671.21 |
| FP       | 40.28   | 37.86   | 42.30   | 42.99   | 45.94   | 44.91   | 45.62   | 47.01   | 46.94   | 43.76   |
| MR       | 35.41   | 31.14   | 29.08   | 32.84   | 35.70   | 37.96   | 45.85   | 45.81   | 47.61   | 37.93   |
| FR       | 0.80    | 0.83    | 0.84    | 0.82    | 0.80    | 0.78    | 0.73    | 0.73    | 0.72    | 0.78    |
| RR       | 0.25    | 0.21    | 0.19    | 0.23    | 0.26    | 0.29    | 0.38    | 0.37    | 0.40    | 0.29    |
| CR       | 0.10    | 0.09    | 0.08    | 0.09    | 0.10    | 0.11    | 0.13    | 0.13    | 0.14    | 0.11    |
| Scoring  | 275     | 425     | 475     | 425     | 375     | 275     | 275     | 275     | 275     | 275     |
| Class    | II      | II      | II      | II      | II      | II      | II      | II      | II      | II      |

aL: fiber length; FP: felting power; MR: Muhlsteph ratio; FR: flexibility ratio; RR: Runkle ratio; CR: coefficient of rigidity.

From the analysis, it can be concluded that wood fibers of binuang are classified into Quality Class I (Table 4). Binuang fiber was longer, and its fiber wall was thinner compared to the jabon. Since these fibers tend to increase from pith to the bark, it can be concluded that binuang wood is still juvenile.

Besides increasing in fiber length, fiber walls thickness of both species also increased from pith to the bark (Figure 3a). Increasing fiber wall thickness resulted in an increase of RR, but a decreasing of FR. Fibers with lower RR are easier to be beaten than the higher one [43]. Based on the RR value, it can be concluded that binuang fibers are more easily beaten than those of jabon fibers.

In both species, the radial variation of fiber wall thickness also affected the radial variation of SG (Figure 3b). The mean values of fiber wall thickness for jabon and binuang wood were 4.15 µm and 2.57 µm, respectively, while the mean values of their SG were 0.35 and 0.23, respectively. The regression analysis showed that the coefficient of determination (R²) of fiber wall thickness to segmentation for jabon and binuang wood were 0.85 and 0.81, respectively, while for SG were 0.77 and 0.69, respectively. It proved that fiber wall thickness and SG were positively correlated with cambial age (segmentation).

Table 4. Fiber quality of binuang.a

| Criteria | 1       | 2       | 3       | 4       | 5       | 6       | 7       | 8       | 9       | Mean       |
|----------|---------|---------|---------|---------|---------|---------|---------|---------|---------|------------|
| L (µm)   | 1328.16 | 1436.08 | 1604.48 | 1697.68 | 1638.82 | 1692.94 | 1924.94 | 2001.79 | 2119.51 | 2122.78    | 1763.80    |
| FP       | 32.81   | 32.92   | 39.34   | 41.51   | 51.14   | 53.07   | 52.86   | 64.26   | 64.19   | 48.01      |
| MR       | 17.77   | 17.99   | 20.32   | 20.08   | 31.00   | 26.58   | 27.28   | 38.45   | 32.54   | 25.78      |
| FR       | 0.91    | 0.91    | 0.89    | 0.89    | 0.83    | 0.86    | 0.85    | 0.78    | 0.82    | 0.86       |
| RR       | 0.05    | 0.11    | 0.12    | 0.12    | 0.21    | 0.17    | 0.18    | 0.28    | 0.22    | 0.17       |
| CR       | 0.05    | 0.05    | 0.05    | 0.05    | 0.08    | 0.07    | 0.07    | 0.11    | 0.09    | 0.07       |
| Scoring  | 475     | 475     | 475     | 475     | 475     | 450     | 500     | 550     | 350     | 500        | 475        |
| Class    | I       | I       | I       | I       | I       | I       | I       | I       | I       | I          |

aL: fiber length; FP: felting power; MR: Muhlsteph ratio; FR: flexibility ratio; RR: Runkle ratio; CR: coefficient of rigidity.
Felting power (FP) is the ratio of fiber length to fiber diameter. The longer the fiber, or the smaller diameter, the higher the FP value. Felting power is associated with the tear strength of pulp in paper manufacturing, where higher FP means lower tear strength [43–44]. The binuang fiber was longer than jabon fiber, therefore, the binuang FP value was higher than that of jabon. Based on the FP value, it can be concluded that binuang fibers are less resistant to the tear compared to those of jabon.

Coefficient of rigidity (CR) expressed density in the pulp, which affects pulp yield and opacity [43]. Jabon fiber had a higher CR than that of binuang. Based on this parameter, paper made from jabon fiber will have higher opacity than binuang fiber. However, the CR of each segment was also varied. In jabon and binuang wood, The CR was higher on the segments that were closer to the bark.

3.3 Juvenile-mature transition

The polynomial regression showed that there was a similar pattern of fiber and vessel length in jabon wood. Fiber and vessel length of jabon began to be constant visually in the seventh segment (Figure 4a and Table 5). The coefficient of determination ($R^2$) between fiber length and segmentation was 0.95, while for vessel length was 0.99. These indicated that there is a very high correlation between fiber and vessel length of jabon wood with segmentation. In contrast to jabon, linear regression was found between fiber and vessel length with segmentation in binuang wood (Figure 4b). The coefficient of determination between fiber length and segmentation was 0.95, however between vessel length and segmentation was only 0.40. It indicated that there was a more decisive factor in vessel length than segmentation.

![Figure 3. Radial variation of fiber wall thickness (a) and specific gravity (b) for jabon and binuang.](image)

![Figure 4. Polynomial regression between fiber and vessel length with segmentation of jabon (a) and binuang (b).](image)
Figure 5. Segmented regression model between fiber (A, B) and vessel (C, D) length of jabon - and binuang with segmentation.
Segmented regression model gave more definite value for the juvenile-mature transition than visual observation [34]. The results showed that the transition point of each parameter was different. These results concur with previous studies where the juvenile-mature transition varied depend on parameters [10,36,45]. For fiber length parameter, it was known that jabon wood had earlier maturation point (segment 6) than vessel length (segment 7) (Table 5 and Figure 5A, 5C). Thus, it is concluded that the transition zone of jabon wood was in-between segments 6 and 7. The present result is different from that was reported by Darmawan et al. [46], where jabon with a diameter of 36–37 cm was juvenile.

Table 5. Estimation juvenile-mature transition of jabon and binuang.

| Model                        | Jabon       | Binuang     |
|------------------------------|-------------|-------------|
|                              | Fiber length| Vessel length| Fiber length| Vessel length |
| Polynomial regression        | 7           | 7           | -           | -            |
| Segmented regression model   | 6.824       | 7.237       | 33.387      | 30.041       |

For binuang, there was an increasing pattern of fiber, vessel length, and the bark. Segmented regression model (Table 5 and Figure 5B, 5D) showed that the transition point from fiber and vessel length occurred in segments 33 and 30, respectively. Thus, it can be concluded that binuang wood in this study is still juvenile because the existing segment was only nine. Boundaries determination of juvenility are definitely difficult because of the nature of wood including the existence of transition zones within a tree [28,33]. The existence of a transition zone is evident in this present study. There is a different transition point (around 1 to 3 segments) from different parameters (Table 5).

Moreover, the different methods also affect the juvenile-mature transition (Table 5). In this current research, polynomial and segmented regression model gave a different value for every parameter. For binuang wood, juvenile-mature transition can’t be determined visually by polynomial regression because the graph is still exhibited an increasing pattern. However, by using the segmented regression model, the juvenile-mature transition for both jabon and binuang woods can be determined. Even though the segmented regression model has a limitation, but this model can be used to predict the boundary of wood juvenility, which is still juvenile. Previous studies also proved that different models or methods gave a different value of juvenile-mature transition [33–36,47]. They used the visual method, Shiokura, segmented regression model, mathematical modeling, polynomial model, nonlinear mixed model, and linear model (piecewise). Therefore, method choice should be based on a clear understanding of the genetic and plants respond to the environment.

4. Conclusions
Fiber quality of jabon and binuang wood were classified into Quality Class II and I for pulp and paper manufacturing, respectively. Even though fiber length and fiber wall thickness varied radially, fiber quality class in all segments of each species was similar. The juvenile-mature transition boundaries of jabon wood occurred on the segment 6 and 7, while the whole binuang wood was still juvenile. The boundary between juvenile and mature wood was affected by parameter and method applied.

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