Pulp and Paper Characteristics of Five Lesser-known Species in Kalimantan: Effects of Re-beating

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Abstract

Five lesser-known species from natural forests in Central Kalimantan, viz., cempaka (*Michelia champaca* Linn), mentawa (*Artocarpus rigidus* Blume), menjalin (*Xanthophyllum excelsum* Miq.), kempili (*Lithocarpus* elegans (Blume) Hatus. Ex Soepadmo), and sempori (*Dillenia* sp.) were evaluated in the laboratory for their specific gravity, fiber morphology, pulping and papermaking properties. In addition, their properties after three-phase beating were also evaluated from a recycled paper point of view. The specific gravity and fiber length range were 0.58~0.68 and 1239~2479 µm, respectively. The highest value in specific gravity was observed in menjalin wood, while the longest fiber was observed in sempori. Kraft pulping with 14% active alkali (as Na_2O), 23% sulfidity, 2 h at the maximum temperature showed that the highest screened yield was determined in cempaka wood (44.29%) with a kappa number of 17.6. The freeness ranges of unbeaten pulp were 675~780m mL CSF. The freeness ranges of 1st, 2nd, and 3rd beating were 539~630 mL, 235~275 mL, and 220~230 mL CSF, respectively. The 1st beating exhibited the best mechanical properties. Among the species, cempaka, kempili, and mentawa showed comparatively high tensile (57~60 Nm/g) and burst index (2.6~3.4 KPa m^2/g), whereas the highest value for tear index (5.02 mNm^2/g) was observed in sempori. A considerable decrease in fiber length, slenderness ratio, and mechanical properties of the paper was observed with an increased beating number. These findings suggest that cutting the fibers or decreasing the slenderness ratio was the main factor causing the strength to decrease.

Keywords: beating degree, secondary fiber, kraft pulping, pulp wood, fiber morphology.

Introduction

The growing consumption of pulp and paper in Indonesia relies mainly on the exploitation of forests for pulp wood and the recycling of fibres. In 2020, Indonesia is projected to produce 20.4 million metric tons of pulp and 19.8 million metric tons of paper (APKI 2014). Globally, recycled paper is becoming an increasingly important fiber source for the pulp and paper industry. Furthermore, the annual consumption of recycled paper (>120 million metric tons) has surpassed that of paper from non-wood sources (Henriksson *et al.* 2009). Increasing the use of lesser-known species and recycled fibers by rationalizing their valorization could allow the conservation of forest resources and bring new properties to wood-based products considering the specific properties of these fibers.

Cempaka (*Michelia champaca* Linn), mentawa (*Artocarpus rigidus* Blume), menjalin (*Xanthophyllum excelsum* Miq.), kempili (*Lithocarpus* elegans (Blume) Hatus. Ex Soepadmo), and sempori (*Dillenia* sp.) are lesser-known native tree species in Central Kalimantan, Indonesia. These species are naturally distributed and abundant in natural forests in Kalimantan. In addition, those species are also planted in other islands in Indonesia. To the best of our knowledge, no information has been published on the wood and pulp properties of these species. Studies of these properties are necessary for the improvement of the availability of pulp raw materials.

Cellulosic fibers obtained from pulping processes must be subjected to physical treatment in order to render them useful for making paper with acceptable properties (Mutje´a *et al.* 2005). These properties can be significantly improved by mechanical treatment of the fibers, a process known as beating or refining. Beating of pulp is a mechanical treatment that causes physicochemical changes in fibers by external and internal fibrillation of the cell wall (Emerton 1957). Beating or refining improves not only the fiber properties but also the paper properties. In some cases, the aim is to shorten fibers that are too long for good sheet formation or to develop properties such as absorbency, porosity, or optical properties for a certain paper grade (Lumiainen 2000). This process is the most energy-intensive in pulp and paper production. However, beating has undesirable effects, such as fiber shortening and the creation of axial micro compressions in the fiber wall (Rosli *et al*. 2011). Some factors, such as the extent of their mechanical and chemical damage and the length of the fibers, affect the strength of paper sheets (Levlin and Soderhjelm 1999). Therefore, it is necessary to study this negative influence with respect to recycled fibers.

In order to obtain accurate data to improve the quality of fibers from the five lesser-known species mentioned above, the goals of the research presently conducted were: (a) to describe the specific gravity and morphology in the wood fiber, (b) to describe the pulp properties from kraft pulping, (c) to discover the beating behaviour and mechanical properties of the paper, and (d) to discover the effect of re-beating on fiber morphology and mechanical properties of the paper. Energy savings and the desired paper properties can be achieved by applying proper beating process conditions, and improper beating cannot be compensated for in the subsequent processing steps.

Materials and Methods

Sample Preparation

Wood samples of cempaka, mentawa, menjalin, kempili, and sempori were collected from the lower part of trees (unknown age, ± 1.3 m above ground) in the natural forest concession managed by PT. Sari Bumi Kusuma, Central Kalimantan. The wood disc was then cut into a strip of 5 cm thickness. The wood strip was converted into chips (3 cm × 2 cm × 2-3 mm) for pulping and blocks (2 cm × 2 cm × 2 cm). The blocks were randomly selected for specific gravity and fiber dimension measurements. The chemicals used for pulping were NaOH and Na_2S (technical grade) whereas for kappa number determination were $KMnO_4$, KI, H_2SO_4, starch, $Na_2S_2O_3$ (PA grade).

Fiber Morphology and Specific Gravity

Fiber dimensions were analyzed from square wood samples measuring 1 mm x 1 mm x 20 mm (tangential, radial and longitudinal directions). The wood samples were macerated with the mixed solution of glacial acetic acid and hydrogen peroxide (1:20, PA grade) and heated at 100°C for more than 4 hours. The stained wood fibers were then placed on deck-glass. The wood fibers of each species were photographed with an optical light microscope (OLM, Olympus BX 51 DP 72, Japan). The dimensions, including fiber length (4 × magnification), cell diameter, cell wall thickness, and lumen diameter (40 × magnification) of wood fibers were examined and recorded (Image Pro Plus V.4.5 software). Determination of the percentage of intact and broken fibers (damage) was performed by 4 × magnification of fiber dimension specimens. Green specific gravity (wet volume/oven-dry weight) was prepared and measured according to British Standard No. 373 (1957).

Runkel ratio, slenderness ratio, coefficient of rigidity, Luce's shape factor, and flexibility coefficient were calculated using the following equations (Tamolang and Wangaard 1961; Dinwoodie 1965; Ogbonnaya *et al.* 1992):

Runkel ratio = Double fiber cell wall thickness/Fiber lumen diameter *(1)*

Coefficient of rigidity = Fiber wall thickness/Fiber diameter *(2)*

Slenderness ratio = Fiber length/Fiber diameter *(3)*

Flexibility coefficient = Fiber lumen diameter/Fiber diameter *(4)*

Fiber dimensional changes after beating were calculated using the following equations:

Fiber dimensional reduction = (Initial dimension from macerated samples – Post-beating dimension) × 100 *(5)*

Fiber dimensional addition = (Post-beating dimension - Initial dimension from macerated samples) × 100 *(6)*

Pulping

Preparation of kraft pulps consisted of white liquor (NaOH and Na_2S). Kraft pulps were processed in a 5-liter KRK laboratory rotary autoclave. The raw material (300 g, oven dry weight) was cooked in the autoclave with a liquor-to-wood ratio of 4:1. The pulp conditions were active alkali 14% as Na_2O and sulfidity of 23%. Pulps were processed for 120 min at 170~180°C with time to maximum temperature was 60 min. The target of kappa number was 18. The pulps were dispersed with a standard pulp disintegrator. Then, the pulps were placed in a No. 100 mesh screen to separate the screened pulps and reject them. The kappa numbers of the screened pulps were determined according to standard test methods SNI ISO 302 (2014).

Niagara Beating

Niagara beating is performed in a batch with a low-consistency pulp. The beating is looped around a well and forced between a rotor bar and a loaded bedplate to generate a mechanical shearing action. Kraft hardwood pulps were loaded into the Niagara beater (KRK, Japan) and refined at 0.3% consistency with a 1 kg load for the first, second, and third beatings. The first beating was conducted for 5 minutes, whereas the second and the third beatings were conducted for another 5 minutes at each phase. Samples for fiber measurement and papermaking were taken from the laboratory beater at the three-phase beating or beating number. The drainage capabilities of the unbeaten and beaten pulps were measured with a KRK Canadian Standard Freeness (CSF) tester according to SNI ISO 5264-1-2011.

Dry Strength Evaluation

Hand sheets of 80 g/m^2 were produced on a sheet former (diameter of 15.9 cm) according to SNI ISO 5269-1-2012. The standard hand sheets were conditioned at 23±2°C and 50±2% relative humidity. The following tests for dry strength (mechanical) properties were determined using standard SNI ISO methods: (i) Tensile strength index, SNI 14-0437-1989-A; (ii) Burst strength index, SNI ISO 2758-2011; (iv) Tear strength index, SNI 14-0436-1989. Strength reduction in the 2nd and 3rd beatings was calculated using the following equations:

Strength reduction = (Strength in 1st beating – Strength in the 2nd or 3r beating) × 100
(7)

Results and Discussion

Specific Gravity and Fibre Morphology

Table 1 shows the mean value of the measured specific gravity of these species from the minimum to the maximum values and their fiber dimensions. The maximum specific gravity value was observed in menjalin (0.68) while the minimum was in sempori wood (0.58). This specific gravity ranges are slightly higher compared to commonly specific gravity for pulp and paper purposes i.e., 0.35~0.65 (Miranda *et al*. 2012). Among five wood species, sempori has the longest fiber length (2479 µm) followed by menjalin (1587 µm). Kempili has the highest value of fiber diameter, fiber lumen diameter, and fiber wall thickness. The correlation between specific gravity and cell wall thickness was unclear among those species. Menjalin had the highest specific gravity level but the cell wall thickness was lower compared to the other species. It is assumed that extractives content also affects the value of specific gravity. With regard to derived values, slenderness ratio of sempori was the highest (111.9) whereas the highest flexibility coefficient (0.70) was found in mentawa. Furthermore, the lowest value of Runkel ratio (0.58) was found in mentawa and sempori, whereas the lowest coefficient rigidity (0.19) was calculated in menjalin and sempori.

A positive correlation was found between fiber length and burst strength (Ona *et al*. 2001) as well as between fiber length and tear strength (Shmulsky and Jones 2011). Thick-walled fibers are not expected because it will produce paper with low burst and tensile strength (Shmulsky and Jones 2011). Furthermore, the Runkel ratio measures the suitability of fiber for paper production, the slenderness ratio (Peteri coefficient) measures the tear property of pulp in paper production, the flexibility coefficient measures the strength properties of paper, and the coefficient of rigidity measures the tensile strength of fiber (Yanez-Espinosa *et al.* 2001). On the basis of derived values, the relatively low values in Runkel ratio and coefficient rigidity, as well as high values in slenderness ratio suggests that sempori and mentawa wood would exhibit better paper mechanical properties.

Figure 1 shows the morphology of these species from the shortest fiber to the longest one, respectively. Each wood fiber species, exhibits specific characteristics. There were three fibers that possessed a distinct and short tail proportion in one end, i.e., kempili, menjalin, and sempori. Sempori has a long fiber, which is very easy to distinguish from others. This fiber shows a rather special characteristic because the size of the fiber is close to conifer, such as *Pinus* merkusii. Mentawa and cempaka showed more tapered tails on both ends.

Table 1. Specific gravity and morphology of wood fibers of five species from natural forest

No	Wood characteristics	Sempori	Cempaka	Mentawa	Kempili	Menjalin
1	Specific gravity	0.58	0.60	0.66	0.66	0.68
2	Fiber dimension					
	Fiber length (µm)	2479	1316	1230	1395	1587
	Fiber diameter (µm)	22.14	19.45	17.83	26.82	19.28
	Fiber lumen diameter (µm)	13.55	10.38	10.52	15.69	11.84
	Fiber wall thickness (µm)	4.29	4.53	3.65	5.56	3.72
3	Derived values					
	Runkel ratio	0.58	0.87	0.58	0.74	0.62
	Slenderness ratio	111.97	67.65	68.99	52.01	82.33
	Flexibility coefficient	0.65	0.53	0.70	0.55	0.61
	Coefficient of rigidity	0.19	0.23	0.20	0.20	0.19

Figure 1. Morphology of wood fibers of five species from natural forest. Left to right: mentawa (*Artocarpus rigidus* Blume), Cempaka (*Michelia champaca* Linn), kempili (*Lithocarpus* elegans (Blume) Hatus. Ex Soepadmo), menjalin (*Xanthophyllum excelsum* Miq.), and sempori (*Dillenia* sp.)

Pulp Properties

The pulp yield and kappa number of five species were measured to evaluate them as pulping raw materials. As shown in Table 2 (from the lowest specific gravity to the highest one), the minimum pulp screened yield was observed in mentawa pulp (24.39%) and sempori pulp (26.96), and the maximum value was observed in cempaka pulp (44.20%). Kempili, menjalin, and sempori showed high levels of rejects (40~44%). Mentawa showed the highest kappa number (19.44), whereas kempili showed the lowest (17.22) among these five species. Although the kappa number was mostly at the target value (18), only cempaka gave the yield exceeding 40%. The pulp yield obtained under these operating conditions indicates that the concentration of active alkali is probably too low to obtain commercial level of yield (45~50%). It was assumed that the wood with high value of specific gravity might need more chemical concentration in this experiment. Mentawa and sempori showed almost similar pulp yield but had huge difference in rejects.

High value of the specific gravity of the wood results in high consumption of chemicals (Gomide *et al.* 2010). Low density will result in a lower kraft yield (Haroen 2017). This pattern of pulp yield cannot be explained by the variation in specific gravity (Table 1). On the other hand, a higher amount of lignin results in lower pulp yield (Shmulsky and Jones 2011) as well as lower paper mechanical properties (Fengel and Wegener 1989). Therefore, another factor, such as the chemical properties of these species, should be investigated to explain the variation in yield or kappa number.

Table 2. Pulp properties after kraft cooking of five species from natural forest.

No	Species	Screened yield (%)	Reject (%)	Kappa Number
1	Sempori	26.96	42.90	18.50
2	Cempaka	44.20	6.13	17.60
3	Mentawa	24.39	25.59	19.47
4	Kempili	36.94	44.82	17.22
5	Menjalin	33.74	40.22	19.14

Beating Properties

Freeness tests are commonly used to measure the effects of beating in an indirect way. The pulp freeness was measured as Canadian Standard Freeness (CSF). As shown in Table 3, the degree of beating is presented as a function of the beating number applied. The freeness, which was principally influenced by fiber fibrillation and the number of fine elements, was 675~780 mL CSF on average for the unbeaten pulp. The average range values decreased until it reached 220~230 at the 3rd beating (Table 6). For unbeaten pulp, sempori and menjalin gave the highest value of CSF (780 and 750 ml CSF, respectively), whereas cempaka gave the lowest value (675 ml CSF). The low values indicate more water was retained on the fiber surfaces. It is expected that the long fiber length in sempori wood would give the comparatively high rate in the freeness test.

The effect of pulp refining on fiber properties is that fiber shortening produces small particles (shorter than 200 μm) (Tonoli *et al.* 2013). They are commonly referred to as fines, which also contain band-like materials from both the primary and secondary wall layers of the fibers (Somboon *et al.* 2007). These fines increase the water retention of the web, fill the gaps between fibers, and lead to a reduction in CSF data. The reduction in freeness is visible as a function of beating. As shown in Table 3, as the number of beatings was increased, the degree of beating was reduced. Kempili showed a considerable reduction in beating degree after re-beating among these species. Fibers with low intrinsic viscosity (lower molar mass of cellulose and hemicellulose) were more easily damaged during refining than fibers with high intrinsic viscosity (Molin *et al.* 2004). The comparatively low value of kappa number with lower lignin content (less than 25%) in kempili may make the fiber less coarse and less resistant to mechanical action. In the third beating, the beating degree levels among the observed species were in slight differences. This indicates that the need of energy is almost similar to achieving 220-230 in the 3rd beating. Technically, high dewatering is preferable, while the reduction in draining of the pulp caused by refining (measured by freeness) is not desirable in the papermaking process.

Table 3. Beating degree (mL CSF) of kraft pulps from five species grown in natural forest

No	Species	Unbeaten/ initial	1st	2nd	3rd
1	Sempori	780	660	255	225
2	Cempaka	675	550	275	220
3	Mentawa	710	550	255	225
4	Kempili	700	530	235	230
5	Menjalin	750	640	255	225

Effect of Re-beating on Fiber Morphology

Beating degree is one of the main indicators of pulp dewatering performance, which can comprehensively reflect the degree of fiber cutting, swelling, and fiber fibrillation (Shi and He 2008). By observing cell morphology, a larger proportion of fibers were damaged by the increasing number of beating or refining actions during the pulping process, which was performed to produce a strong fiber bonding and a good surface smoothness for paper sheet (Casey 1980; Smook 1989). Fibers were damaged after beating, and the amount of damaged fibers increased with the number of beating (Table 4). The highest proportion of damaged fiber in the 3rd beating was observed in sempori samples, whereas the least was observed in kempili. In addition, sempori wood had the highest value of damaged fibers in each phase of beating, whereas kempili had the lowest damage in the 2nd and 3rd beatings. Based on the values of the first beating, mentawa, kempili, and menjalin had 17 to 21% damaged fibers or about double in the 3rd beating. Although it is uncertain, it is assumed that the low specific gravity value in sempori caused less resistance to mechanical action and generated more damaged fibers, whereas the higher thickness of the wall of kempili would cause the least damage in the 3rd beating.

Table 4. Damage proportion (%) in fiber of kraft pulp at three-step beating from five species grown in natural forest

No	Species	1st		2nd		3rd	
		Intact	Damage	Intact	Damage	Intact	Damage
1	Sempori	75.67	24.33	69.50	30.50	51.06	53.92
2	Cempaka	92.92	7.08	83.53	16.47	74.84	25.16
3	Mentawa	87.65	12.35	81.79	18.21	80.48	19.52
4	Kempili	91.39	8.61	89.12	10.88	82.40	17.60
5	Menjalin	89.07	10.93	85.35	14.65	78.81	21.19

After evaluating the damage, the dimensional changes on the fibers were also measured (Fig. 2). The length and thickness of the fibers decreased, while their diameter or width and lumen showed an increasing trend with an increasing number of beating (Fig. 2). Therefore, at the 3rd beating, fiber diameter, and lumen reached maximum values, while fiber length and wall thickness obtained minimum values. However, slight changes were observed in kempili and sempori for fiber diameter as well as cempaka and menjalin for fiber wall thickness at each stage of beating. Considerable decrease in fiber length was observed in maceration sample to 1st beating for mentawa and menjalin samples. A remarkable reduction in fiber wall thickness was observed only in kempili fibers. The calculation of fiber dimension reduction or addition at the 3rd beating based on the values of the control (macerated samples) is presented in Table 5. The highest reduction in fiber length as well as addition in fiber diameter and fiber lumen diameter was observed in menjalin. In contrast, the highest reduction in fiber wall thickness (29.22%) was found in kempili. In this experiment, menjalin had the highest value of specific gravity while kempili had the highest value of fiber diameter, fiber lumen diameter, and fiber wall thickness. Therefore, this indicates the relationship between specific gravity or fiber wall thickness and the dimensional changes after beating.

The effects of beating on the derived values were generally as expected, with the gradual slenderness ratio, Runkel ratio, coefficient rigidity values decreasing (Figure 2a) and flexibility coefficient values increasing (Fig. 1). The magnitudes of the dimensional changes were measured at the 3rd beating based on the values of the maceration samples (Table 5). Observations showed that mentawa and sempori pulps had greater decreases in coefficient rigidity (22~23%), while sempori pulp in Runkel ratio (24.95%) and slenderness ratio (41.43%). The highest increasing level in flexibility coefficient (9.90%) was observed in the kempili wood. There is no clear pattern of dimensional change levels with the specific gravity of these species.

Table 5. Dimensional changes (%) of kraft pulp at third step beating from five species grown in natural forest

No	Fibre properties	Sempori	Cempaka	Mentawa	Kempili	Menjalin
1	Fibre length	-24.00	-12.68	-19.2	-19.13	-29.23
2	Fibre diameter	+3.43	+6.06	+16.09	+0.63	+17.47
3	Fibre lumen diameter	+18.67	+16.47	+3.46	+21.79	+31.75
4	Fibre wall thickness	-21.06	-5.82	-10.70	-29.22	-5.26
5	Runkel ratio	-24.95	-18.53	-21.40	-15.50	-9.53
6	Slenderness ratio	-41.43	-17.64	-30.41	-19.66	-39.75
7	Flexibility coefficient	+7.58	+8.80	+5.27	+9.90	+5.37
8	Coefficient of rigidity	-22.68	-11.15	-22.92	-14.42	-19.17

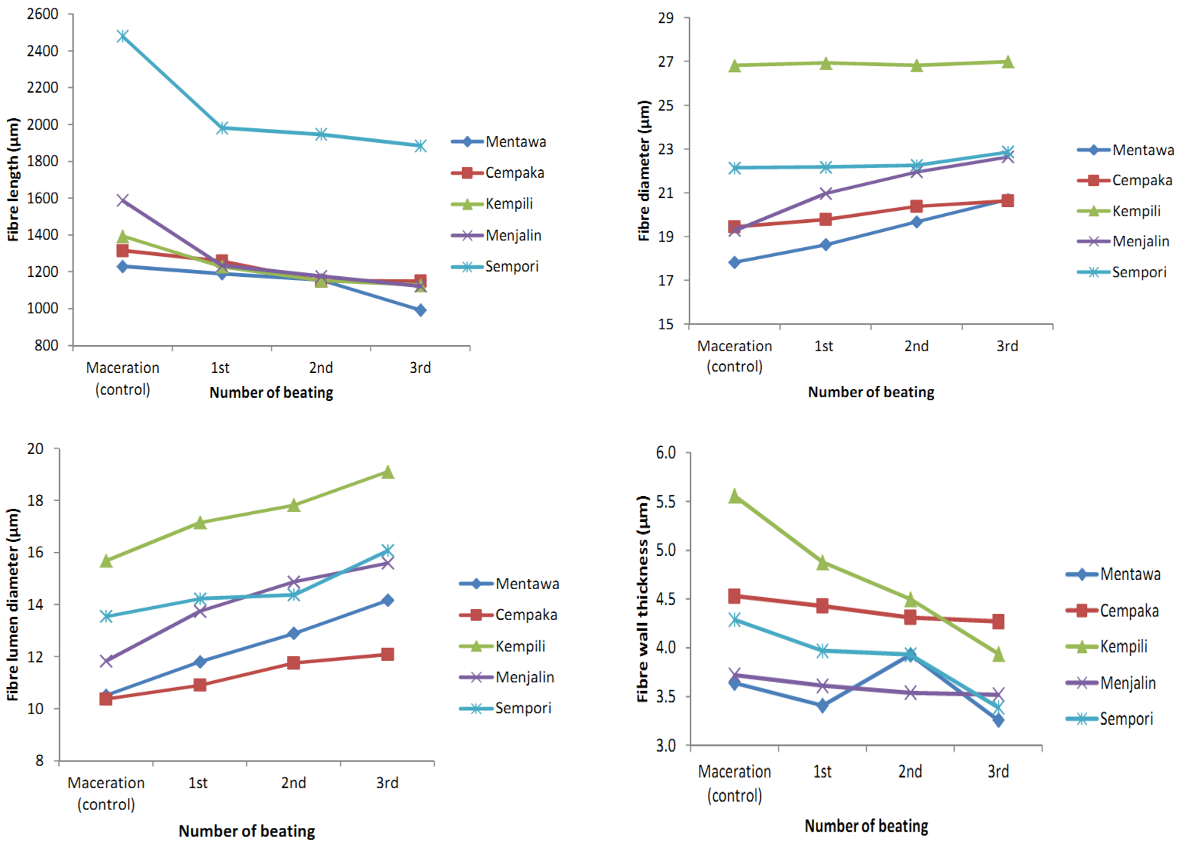

Figure 2. Fiber dimension of kraft pulp at three-step beating from five species grown in natural forest

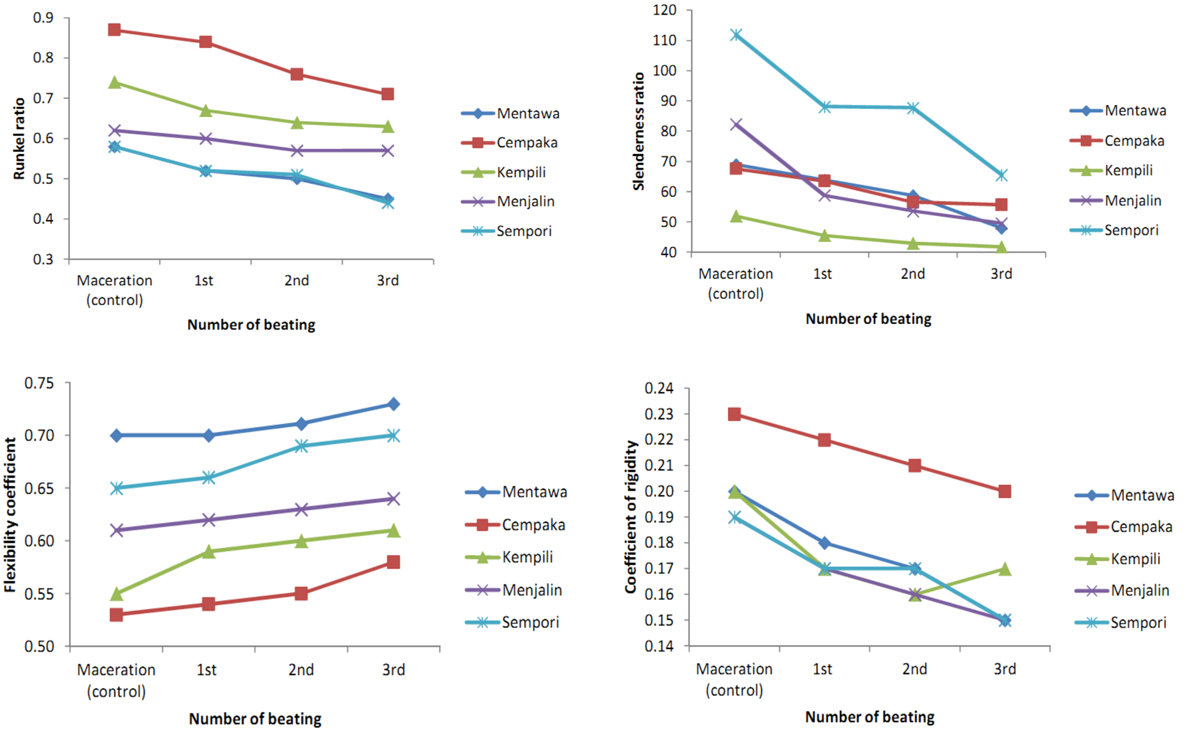

Figure 3. Derived values of kraft pulp at three-step beating from five species grown in natural forest

Paper Mechanical Properties

The differences in paper strength among the five hardwood pulps were as expected. The initial quality and strength of the fibers, as well as the bonding between them, affect the strength properties of the paper. Paper made from unbeaten fibers has low bulk, low strength, and a rough surface, which are commonly undesirable for various end products. The comparison among the species in mechanical properties of the sheet at the 1st beating is presented in Table 1. The maximum level in the tensile index were observed in cempaka and kempili, while the maximum level in the burst index was observed in cempaka and mentawa. Sempori had the highest value in tear index. Tensile index and tear index are two important indicators of physical properties of paper, and they depend on the fiber strength, fiber binding force, and the fiber length (Zhang and Xia, 2014; Seth 1990). The relatively high values in fiber length and slenderness ratio in simpori may explain the high value of tear strength. Cempaka and kempili had the highest fiber wall thickness value, which was related to their high level of tear index. In addition, cempaka and mentawa had the lowest values in fiber diameter in the first beating process, which might relate to their high value in the burst index.

Based on the Indonesian National Standard (SNI) for leaf (hardwood) bleached kraft pulp in terms of tear index, no species met the standard. Sempori and menjalin also failed to meet the standards for tensile and burst indices. This suggests that cempaka, mentawa, and kempili have more opportunities to be developed as raw materials for pulp and paper. However, this experiment was based on only one pulping condition. Since pulp and paper quality also depends on process factors, further work should be conducted for process optimization for each species.

Table 6. Paper mechanical properties at first beating step from five species grown in natural forest

No	Mechanical Properties	Tensile index (Nm/g)	Burst index (KPa m^2/g)	Tear index (mNm^2/g)	SG
1	Sempori	41.92	1.83	5.02	0.58
2	Cempaka	60.94	3.49	3.75	0.60
3	Mentawa	57.51	3.48	4.30	0.66
4	Kempili	60.06	2.65	4.49	0.66
5	Menjalin	42.12	2.27	4.21	0.68
6	Leaf bleached kraft pulp (SNI) [a]	45.00	2.50	5.50	

Remark: a = Indonesia National Standard (SNI 6107, 2009), SG = specific gravity

Effect of Re-beating on Mechanical Properties

Beating increased the hydrogen bonding capacity of the fibers, and consequently the strength of the fiber network but decreased the strength of individual fibers (Tonoli *et al.* 2013). The bonding between fibers is increased because of an increase in fiber collapsibility, specific surface area, and flexibility. Beating process conditions must be selected to maximize the desired effects and minimize the undesired effects (Hietanen and Ebeling 1990). Mechanical properties (i.e. tensile index, burst index, and tear index) decreased with the increased beating number (Table 7). The strength values were highest for the paper sheet subjected to the 1st beating (530~660 mL CSF) compared to the lowest for the 3rd beating (220~230 mL CSF). The degree of reduction among the species was almost similar for tear index, but it varied for tensile and burst indices. The magnitude of reduction (percentage) at the 2nd and 3rd beatings based on the strength values at the 1st beating is summarized in Table 6. In terms of tensile index, menjalin wood showed the lowest level of reduction, indicating it has more resistant fibers to mechanical actions. The different species were observed to give the lowest reduction at the 2nd and 3rd beatings for burst and tear indices.

Table 7. Decrease of paper mechanical properties (%) at second and third beating steps

No	Species	Tensile index		Burst index		Tear index	
		2nd	3rd	2nd	3rd	2nd	3rd
1	Sempori	35.06	47.11	26.28	28.85	41.65	71.05
2	Cempaka	33.91	43.61	49.64	54.71	31.46	49.44
3	Mentawa	23.83	52.49	24,21	47,04	27.72	61.82
4	Kempili	42.71	51.94	35.01	44.13	41.72	62.87
5	Menjalin	10.66	16.36	18.56	37.69	43.06	62.34

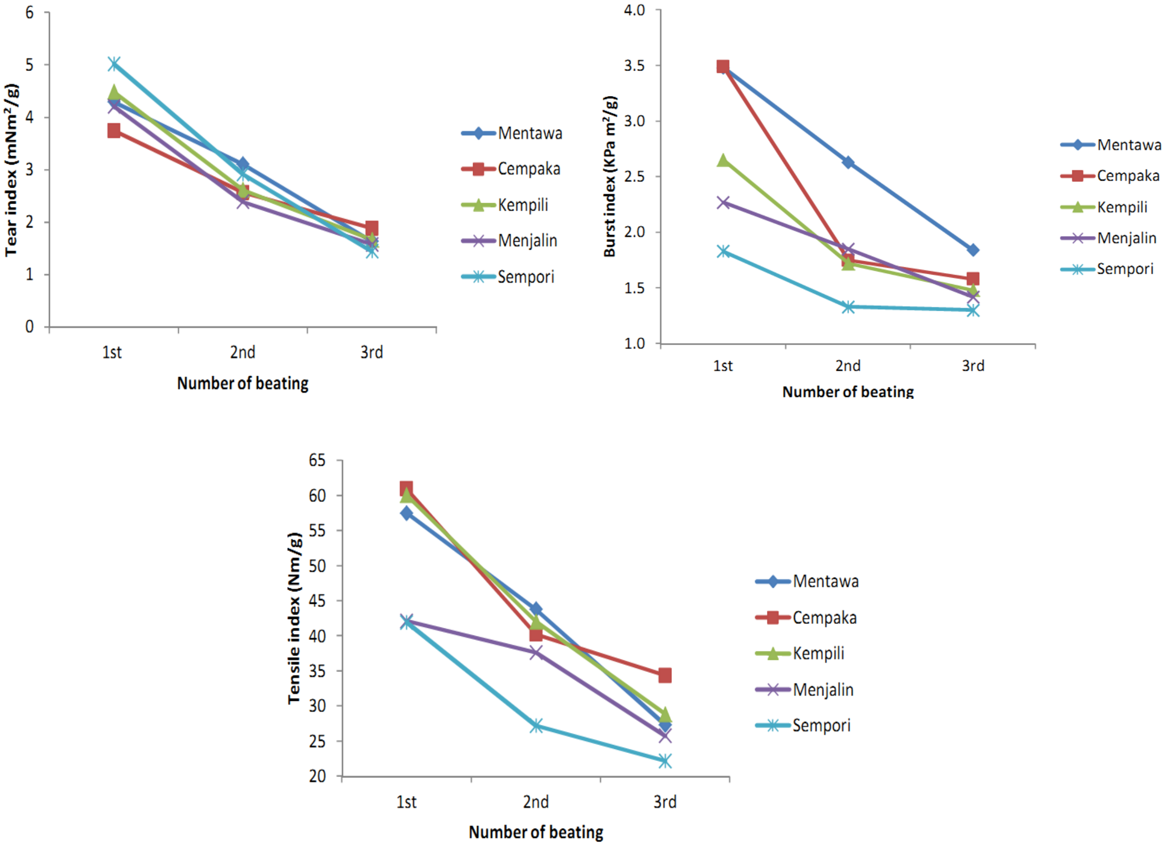

Figure 4. Strength properties of paper at three-step beating

The main factors affecting the tensile index of paper were the strength of the fiber combination and the average fiber length (Gao *et al.* 2012). The change in tear index should also be attributed to the derived values of the fibers. When the beating number was only 1st, the strength of a single fiber was good, while there was little friction between fibers, resulting in a lower tear index. As the beating number increased, the slenderness ratio (the ratio of fiber length to fiber width) decreased, while their strength and the combination and friction between fibers increased. Technically, the higher values of flexibility coefficient along with the lower values of Runkel ratio and rigidity coefficient after beating would increase the paper strength. On the contrary, the decreasing value of the slenderness ratio after beating would decrease the paper strength. Thus, it is assumed that the changes in the slenderness ratio that was reduced had more considerable effect as compared to the other derived values.

As the number of beating increased, the beating degree of the pulp continuously decreased, while the average fiber length became shorter and shorter (Fig. 2). Fiber cutting or fiber length reduction could negatively affect the paper strength values, such as tensile index and tearing resistance (Rosli *et al.* 2011). Under the influence of the fiber bonding force and average fiber length, the tear index decreased after the point of maximum value, which indirectly indicated that excessive fiber cutting would decrease the tear strength of the paper. When the average fiber length decreased, it became the main factor affecting the burst index and caused its decrease (Gao *et al.* 2012). Burst index, which analyses the resistance to a uniformly distributed pressure under test conditions, is positively influenced by the fibrillation promoted by the refining process and negatively influenced by the shortening of the fiber length (Mutje'a *et al*. 2005).

Beating or refining both causes damage to the fibers (fiber shortening, fiber damage) and increases the bonding strength (Molin *et al.* 2004). Optimal beating is therefore an optimization of parameters to obtain maximum bonding strength without an excessive decrease in fiber strength and more energy savings. It is expected that wood with high specific gravity would need more intense beating. In terms of production, the 1st beating produced the best strength of paper sheet and consumed less energy for all species. However, additional treatments are necessary for recycled paper purposes, which require multiple beatings due to considerable strength reductions. In previous work, it was found that the maximum level of tensile and burst indices was observed in the 200~300 mL CSF range, while the tear index was observed in the 400~600mL CSF range for *Acacia mangium, Acacia auriculformis*, and Acacia hybrid pulps (Yamada *et al.* 1992). In addition, the paper strength is set at 300 ml CSF in SNI. It is uncertain whether the range of 530~660 mL CSF is optimal for higher wood density such as these observed species. Therefore, future studies should employ a wider range of wood density to confirm this hypothesis.

Conclusions

Specific gravity, fiber morphology, and pulp and paper properties were determined for five lesser-known species - mentawa, cempaka, kempili, menjalin, and sempori. These species showed high specific gravity values (0.58~0.68) for pulp and paper purpose and potential values for fiber length (1239~2479 µm) and derived fiber values, Runkel ratio of 0.58~0.87 and slenderness ratio of 52~112. The pulp screened yield and kappa number values were 24~44 and 17.2~19.4, respectively. After three phases of beating, it showed that damaged fibers, as well as fiber length, fiber wall thickness, Runkel ratio, slenderness ratio, and coefficient rigidity, decreased with increasing beating number. Regarding strength properties, cempaka, kempili, and mentawa woods were characterized as sheets with higher tensile and burst indices. The strength values were highest for the paper sheet subjected to the 1st beating (530~660 mL CSF) compared to the lowest at the 3rd beating (220~230 mL CSF). It is noticed that decreasing the slenderness ratio level had a more significant effect compared to other derived values.

Acknowledgements

The authors wish to thank Yudhi Hendro Sulistianto, Susilo Purnomo, and Saminto from PT Sari Bumi Kusuma for generously providing wood samples.

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