CHEMICAL AND KRAFT PULP PROPERTIES OF CULMS FROM THREE BAMBOO SPECIES NATURALLY GROWING IN LOMBOK ISLAND, INDONESIA

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Chemical and kraft pulp properties of culm were investigated in three bamboo species (*Bambusa vulgaris*, *Bambusa maculata* and *Gigantochloa atter*) naturally grown in four different provenances of Lombok Island, Indonesia. The among-provenance variations of these characteristics were also evaluated. The amounts of chemical components (extractives, ash, Klason lignin, holocellulose, and α-, β- and γ-cellulose) in these three species were in the range of those values in the same genus. Kraft pulp yield and kappa number ranged from 49.0 to 52.3% and from 18.7 to 22.3, respectively. Variance components of the provenance in mixed-effect models were large in several chemical components, suggesting that these properties vary among provenances due to differences in their genetic backgrounds. Thus, provenance selections should be conducted to effectively utilize bamboo culms for chemical products.

Keywords: *Bambusa vulgaris*, *Bambusa maculata*, *Gigantochloa atter*, chemical components, kraft pulp

INTRODUCTION

Bamboo is one of the promising biomass resources due to its fast-growing nature compared to woody plants.[1-4] The bamboo culm has recently been utilized as a modern construction material, the raw material for pulp and paper, and other chemical raw materials, based on the scientific surveys of culm properties.[2,4-8] However, the abundant bamboo culm resources found in rural areas of Southeast Asian countries are not effectively utilized because they are often limited to traditional use at the local level. If the bamboo culm resources in the rural area can be effectively utilized, the rural economy could also develop in Southeast Asian countries.

Bamboo culm properties vary at different levels.[9] For example, among-provenance variations (or geographic variations) were found in several properties of bamboo culms, even in a single species.[10-13] Understanding the among-provenance variations is essential for effectively utilizing bamboo culm as a modern material. There are several reports on geographic variations of chemical properties in the culm of bamboo growing in China.[10,11] Wang *et al.*[11] reported significant differences in chemical properties (amounts of SiO_2, ash, organic-solvent extractives, lignin, and holocellulose) in naturally grown *Dendrocalamus giganteus* among three different provenances in China. We previously investigated the geographic variation of bamboo culm properties in three bamboo species: *Bambusa vulgaris*, *Bambusa maculata*, and *Gigantochloa atter*, naturally grown in Lombok Island, Indonesia.[12,13] Relatively large geographic variations were found in the green moisture content and basic density in *G. atter*, although the main variations of these properties were found among individual culms in the three species.[12] Similar results were obtained in the anatomical characteristics and mechanical properties of the three species.[13] Unfortunately, we did not examine the geographic variation of chemical properties in the three bamboo species naturally grown on Lombok Island, Indonesia. To utilize the local bamboo resources, among-provenance variations should be clarified for comprehensive culm properties, including chemical components.

In the present study, we focus on the chemical and kraft pulp properties of bamboo culms, to utilize the culms for producing chemical products. By using three bamboo species, *B. vulgaris*, *B. maculata*, and *G. atter*, which were naturally grown in Lombok Island, Indonesia, we tried to clarify if (*i*) there are significant differences in chemical and kraft properties among the three species, (*ii*) there are significant relationships between chemical properties and kraft pulp properties, and (*iii*) there are among-provenance variations in chemical properties, as well as physical and mechanical properties. Finally, the effective utilization of culms from the three bamboo species was discussed based on the results. Hopefully, the findings of the study would of help in the development of the rural economy in Southeast Asian countries, by providing insights into possible uses of abundant bamboo culm resources in these areas.

EXPERIMENTAL

Materials

Culms of three bamboo species (*Bambusa vulgaris* Schrad. ex J.C., *B. maculata* Widjaja, and *Gigantochloa atter* (Hassk) Kurz ex Munro) were collected from natural bamboo stands located in four provenances (Provenance I, II, III, and IV) of Lombok Island, Indonesia (Fig. 1).[12,13] All culms were obtained from four-year-old bamboos.[12,13] Five individuals for each species and provenance (a total of 20 individuals in a species) were used in this study. The 50 cm length samples were collected from 2 m above the ground. The samples with nodes were split and then used for the following experiments.

Amounts of chemical components

Amounts of hot-water extractives, 1% NaOH extractives, organic-solvent (95% ethanol-toluene) extractives, Klason lignin, holocellulose, α-, β- and γ-cellulose, and ash were determined for the bamboo culms, according to the method for determining wood chemical components described by Kuroda.[14] The bamboo meal was prepared from the split culms (without nodes) in a mill (P-14, Fritch, Idar-Oberstein, Germany). The obtained bamboo meal was sieved, and then the fraction between the mesh sizes from # 42 to #80 was used in the present study. In this study, the hemicellulose content was defined as the subtracted value of α-cellulose from holocellulose.

The bamboo samples (1.0 g) were boiled with 100 mL of distilled water in a 200 mL Erlenmeyer flask connected with a Liebig condenser for three hours to determine the hot-water extractive contents. To determine 1% NaOH extractive contents, 1.0 g of bamboo samples were heated with 100 mL of 1% NaOH (Kanto Chemical Co., Tokyo, Japan) aqueous solution for one hour in a water bath at 80 °C. A Soxhlet extractor was used to determine the ethanol-toluene extractives. Bamboo samples (5.0 g) were treated with a 120 mL mixture of 95% ethanol (EtOH) (Kanto Chemical Co., Tokyo, Japan) and toluene (Kanto Chemical Co., Tokyo, Japan) (1:2, v:v) for six hours using the extractor. The solvent was evaporated by a rotary evaporator (N-1100, EYELA, Tokyo, Japan).

Organic solvent extractives-free bamboo powder (1.0 g) was used to determine the Klason lignin contents. One g of bamboo samples was treated with 20 mL of 72% H_2SO_4 (Kanto Chemical Co., Tokyo, Japan) for four hours at room temperature. Then, the concentration of H_2SO_4 was diluted to 765 mL by adding distilled water, and the diluted samples were boiled for two hours.

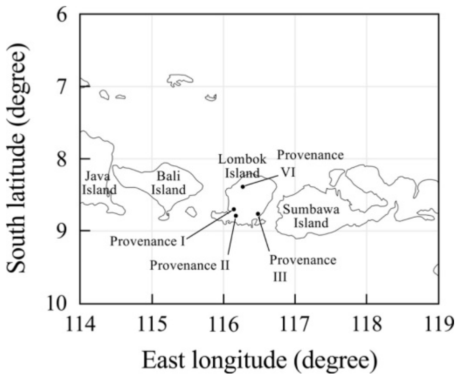

Figure 1: Sampling locations for three bamboo species used in the present study[12,13]

Holocellulose contents were determined by the following methods: 2.5 g of organic solvent extractives-free samples were put in a 300 mL Erlenmeyer flask with 100 mL distilled water, 0.2 mL CH_3COOH (Kanto Chemical Co., Tokyo, Japan) and 1.0 g $NaClO_2$ (Kanto Chemical Co., Tokyo, Japan) and heated in a water bath at 70 °C. The chemicals were added to the flask every hour for three hours.

The α-cellulose contents were determined using a holocellulose sample. The samples (1.0 g) were put in a 50 mL beaker, then 25 mL 17.5% NaOH-aqueous solution was added. The samples were kept for four minutes, and then homogenized by a glass stick for five minutes. After 21 minutes, 25 mL of distilled water was added to the suspension and left for five minutes. The treated samples were filtrated and washed with 200 mL of distilled water. The solution was used for the β- and γ-cellulose contents. The residuals were treated with 40 mL of 10% CH_3COOH and washed with 1000 mL distilled water. The solutions were diluted to 800 mL by adding distilled water. The 40 mL of 30% CH_3COOH was added, and the solutions were heated. After cooling, solutions were filtered through a paper filter (No. 2, Whatman, Toyo Roshi Kaisha Limited, Tokyo, Japan) to determine the β- and γ-cellulose.

To determine the ash content, a bamboo sample (1.0 g) was heated by a muffle furnace (FO100, Yamato, Tokyo, Japan) at 600 °C for one hour.

Kraft pulp properties

Kraft pulp was prepared using the method described in previous papers.[15-17] Small stick samples without nodes (ca. 20 mm in the longitudinal direction and 1 by 1 mm^2 in the transverse section) were prepared from the bamboo culm. To facilitate comparison between the kraft pulp properties of bamboo culm and those of wood, the following single kraft pulping condition that described in previous research[15-17] was used here. Cooking liquor with a 16% active alkali (AA) charge and 25% sulfidity index was used for kraft pulping. Oven-dried (105 °C) bamboo culm sticks (5 g) were put in an autoclave (40 mL) with cooking liquor (weight basis mixture ratio of 4 [cooking liquor] to 1 [bamboo culm stick]). Then, the autoclave with the samples inside was heated at 1.7 °C/min from room temperature to 170 °C by an oil bath (OB-BS, Advantec, Tokyo, Japan) and then successively heated at 170 °C for 90 min. Cooked pulp was defibrated by a pestle and a mortar, and then filtrated and washed with a glass filter (1G3) and distilled water. The pulp yield was calculated by the ratio of the oven-dry weight of the obtained pulp to the bamboo samples.

Using the kraft pulp, the kappa number was determined according to Japan Industrial Standards (JIS) (JIS P8211: 2011).[18] One g of oven-dried kraft pulp sample was added to mixture of 50 mL of H_2SO_4 and 50 mL of 0.02 M $KMnO_4$ solution (Fujifilm Wako Pure Chemical Corporation, Osaka, Japan) in a 1 L conical beaker. The solution was diluted to 500 mL by adding distilled water, and then the suspension was mixed with a magnetic stirrer for 10 min. The suspension was mixed with 10 mL of 1M KI solution (Kanto Chemical Co., Tokyo, Japan). The mixture was then titrated using 0.2 M $Na_2S_2O_3$ solution (Fujifilm Wako Chemicals, Osaka, Japan) until the color changed. The kappa number was calculated by the following equations:

$$\mathrm{KN} = p \times f / w \quad (1)$$

$$p = (b - a)\, C / 0.1 \quad (2)$$

where KN is kappa number, p is the volume of 0.02 M $KMnO_4$ solution (mL) consumed by pulp sample, w is oven-dried kraft-pulp weight (g), b is the volume of 0.2 M $Na_2S_2O_3$ solution consumed in the blank determination, a is the volume of 0.2 M $Na_2S_2O_3$ solution (mL) consumed by kraft-pulp sample, C is molar concentration (M) of $Na_2S_2O_3$ solution, and f is a correction factor to 50% (mass/mass) $KMnO_4$ consumption which depending on the value of p.

Statistical analysis

Statistical analysis was conducted using R software.[19] To compare the mean values of measured properties among species, the Tukey-Kramer test ($p < 0.05$) was applied. Pearson's correlation coefficient was calculated to evaluate the relationships between measured properties. Among-provenance variations of measured properties were evaluated by developing the intercept-only linear mixed-effect model using the lme4 package and lmerTest package.[20] The developed model was as follows:

$$y_{ij} = \mu + Provenance_j + e_{ij} \quad (3)$$

where y_{ij} is the measured culm property of the ith individual bamboo within the jth provenance, μ is the grand mean value of the property, $Provenance_j$ is the random effect of the jth provenance, and e_{ij} is the residual. The variance component ratio of the provenance (VC_p) was calculated by the following formula:[21]

$$VC_p\ (\%) = V_p / (V_p + V_e) \times 100 \quad (4)$$

where V_p is the variance component of the provenance, and V_e is the residual variance.

RESULTS AND DISCUSSION

Amounts of chemical components

Table 1 shows the statistical values of measured properties in this study. Hot-water extractives, 1% NaOH extractives, and organic-solvent extractives ranged from 8.2 to 9.2%, 21.7 to 24.5%, and 3.0 to 5.4%, respectively. Two *Bambusa* species show significantly higher amounts of 1% NaOH and organic-solvent extractives than *G. atter*, while no significant difference was found in hot-water extractives among the three species. The mean values of amounts of ash, Klason lignin, and holocellulose showed no significant differences among the three species, being around 2%, 26%, and 75%, respectively. The amount of α-cellulose in *G. atter* (51.9%) was significantly higher than that of the other two *Bambusa* species (49.8% in both species), whereas the opposite tendency was found in hemicelluloses. The amounts of β- and γ-cellulose ranged from 5.1 to 7.1% and from 17.1 to 21.1%, respectively.

Table 2 shows the amounts of chemical components in *Bambusa* and *Gigantochloa* species. The results obtained in the present study showed almost similar values, except for hot-water extractives and holocellulose. Hot-water extractives and holocellulose were relatively higher than those of the previous studies.[9,10,22-27] However, the values of chemical components obtained in the present study were in the range of previous research.[28]

Kraft pulp properties

The mean kraft pulp yield and kappa number ranged from 49.0 to 52.3% and 18.7 to 22.3, respectively (Table 1). The results of the Tukey-Kramer test showed that *G. atter* had significantly higher pulp yield and lower kappa number than *B. vulgaris*. Bamboo has been used as a raw material for pulp and paper.[2,6,8,24,29,30] In the present study, a relatively higher pulp yield and lower kappa number were obtained in *G. atter* compared to the other two *Bambusa* species (Table 1), suggesting that *G. atter* is the most favorable raw material for kraft pulp among the tested three species. The relatively good kraft pulp properties in *G. atter* might be related to its lower extract and higher α-cellulose contents, compared to the remaining two species. To evaluate the suitability for kraft pulping of the three bamboo species used in the present study, the results were compared with those of wood cooked under the same conditions as those used in this study, although kraft pulp properties with different pulping conditions were reported in many bamboo species by many researchers.[2,6,8,24,29,30] In the comparable previous research, the pulp yield and kappa number were 44.4% and 7.2 in *Eucalyptus camaldulensis*,[16] and 52.9 to 54.8% and 11.5 to 14.3 in *Acacia* species.[17] These results indicate that the three bamboo species in this study could become alternative raw materials for kraft pulp production in the tropical region.

Correlation coefficients between kraft pulp properties and selected chemical properties are shown in Table 3. With a few exceptions, no significant correlations were found between kraft pulp properties and chemical properties in *B. maculata* and *G. atter*. In contrast, for *B. vulgaris*, pulp yield was correlated with amounts of Klason lignin ($r = 0.565$, $p = 0.009$), hemicelluloses ($r = -0.617$, $p = 0.004$), and α-cellulose ($r = 0.669$, $p = 0.001$), and kappa number was positively correlated with amounts of hot-water ($r = 0.555$, $p = 0.011$) and organic solvent ($r = 0.630$, $p = 0.003$) extractives (Table 3).

Table 1
Mean value and standard deviation of each property in three bamboo species

Property	*B. vulgaris* (n = 20)		*B. maculata* (n = 20)		*G. atter* (n = 19)	
	Mean	SD	Mean	SD	Mean	SD
Hot-water extractives (%)	9.2a	2.0	8.9a	2.3	8.2a	1.8
1% NaOH extractives (%)	24.5a	3.3	24.3a	3.0	21.7b	3.6
Organic-solvent extractives (%)	4.7a	1.8	5.4a	2.0	3.0b	1.2
Ash (%)	2.3a	0.6	2.3a	0.5	2.4a	0.4
Klason lignin (%)	26.4a	1.2	26.3a	3.2	25.6a	1.0
Holocellulose (%)	76.0a	1.3	75.1a	1.8	75.3a	0.9
Hemicelluloses (%)	26.2a	1.2	25.3a	2.1	23.4b	2.3
α-Cellulose (%)	49.8b	1.6	49.8b	1.9	51.9a	2.4
β-Cellulose (%)	5.1b	2.0	7.1a	1.7	6.3ab	1.3
γ-Cellulose (%)	21.1a	2.7	18.2b	3.1	17.1b	2.7
Kraft pulp yield (%)	49.0b	2.3	50.6ab	3.7	52.3a	4.4
Kappa number	22.3a	4.9	21.5ab	4.5	18.7b	4.6

Note: n, number of individual culms; SD, standard deviation. Hemicellulose content was defined as the subtracted value of α-cellulose from holocellulose. The same alphabet letters after mean values indicate no significant differences among species at $p < 0.05$ by the Tukey-Kramer test

Table 2
Amounts of chemical components of culms in *Bambusa* and *Gigantochloa* species

Genus	Species	Amounts of chemical components (%)						Reference
		Hot-water extractives	1% NaOH extractives	Organic-solvent extractives	Holocellulse	Klason lignin	Ash	
Bambusa	*B. balcoa*	3.0	–	4.1	–	25.2	2.4	25
		–	–	4.9	70.5	22.4	1.8	28
	B. chungii	–	23.7 – 26.5	5.6 – 6.4	–	21.3 – 23.9		10
	B. maculata	8.9	24.3	5.4	75.1	26.3	2.3	Present study
	B. spinosa (*B. stenostachya*)	7.5	25.6	4.8	68.5	25.2	2.7	24
	B. tuldoides (*B. blumeana*)	–	–	–	65.7 – 72.6	20.5 – 22.7	–	9
	B. vulgaris	9.2	24.5	4.7	76.0	26.4	2.3	Present study
		–	–	–	67.8 – 69.6	22.7 – 23.9	–	9
		–	–	4. 7 – 5.4	75.0 – 77.2	28.8 – 33.5	–	27
		16.3	–	2.1	–	27.5 – 28.2	4.3	27
	(*B. vulgaris* var. *vitata*)	–	–	1.9 – 2.5	62.0 – 73.8	26.2 – 23.6	–	27
Gigantochloa	*G. apus*	–	–	5.3 – 5.9	71.5 – 72.7	25.5 – 27.3	–	27
	G. atter	8.2	21.7	3.0	75.3	25.6	2.4	Present study
	G. levis	–	–	4.8 – 14.0	83.8 – 89.8	20.3 – 36.0	1.3	26
	G. scortechinii	4.0 – 5.9	18.5 – 20.4	3.0 – 3.7	67.2 – 69.0	27.2 – 28.8	1.1 – 1.2	22
		–	–	5.3	80.6	27.8	2.8	23
		–	–	3.6 – 14.2	70.7 – 75.4	28.7 – 43.7	2.8	26
	G. wrayi	–	–	4.5 – 12.4	82.8 – 84.5	34.6 – 44.2	0.9	26

Note: –, no available data. The scientific name in parenthesis is a synonym of the species and the original scientific name in the reference

Under the same kraft pulping conditions as in this study, no significant correlations were found between kraft pulp properties and basic density or amounts of chemical components in *E. camaldulensis*.[16] On the other hand, the kraft pulp yield of three tropical fast-growing tree species negatively correlated with Klason lignin content, but positively with holocellulose and acid-soluble lignin.[15] In addition, significant correlations were found between kappa number and basic density or amounts of chemical components.[15] The relationships between the measured properties in *B. vulgaris* (Table 3) are similar to those in the three tropical species, but those in the remaining two bamboo species are similar to those in *E. camaldulensis*. These results indicate that the relationships between pulp properties and the amounts of chemical components differed among bamboo species. Thus, further research is needed to clarify the relationships between pulp properties and the amounts of chemical components or culm properties to estimate the pulp properties from other properties easily determined in bamboo species.

Table 3
Correlation coefficients between kraft pulp properties and selected chemical properties in three bamboo species

Factor 1	Factor 2	*B. vulgaris*		*B. maculata*		*G. atter*	
		r	*p*	*r*	*p*	*r*	*p*
PY	FL	0.328	0.158	–0.044	0.855	–0.027	0.913
	BD	0.005	0.984	–0.389	0.090	–0.117	0.633
	HWE	–0.303	0.194	–0.038	0.875	0.083	0.736
	AE	–0.214	0.365	–0.010	0.968	0.124	0.612
	OSE	–0.187	0.430	0.032	0.892	–0.104	0.671
	Ash	0.100	0.674	0.359	0.120	0.115	0.639
	KL	**0.565**	0.009	0.204	0.389	–0.226	0.353
	HC	**–0.617**	0.004	**–0.506**	0.023	–0.056	0.821
	AC	**0.669**	0.001	0.190	0.422	0.105	0.668
KN	FL	–0.362	0.117	–0.378	0.101	–0.119	0.626
	BD	0.385	0.094	0.250	0.288	**0.511**	0.025
	HWE	**0.555**	0.011	0.046	0.846	0.061	0.803
	AE	0.295	0.206	–0.361	0.118	–0.078	0.752
	OSE	**0.630**	0.003	–0.056	0.814	–0.197	0.418
	Ash	–0.343	0.139	0.020	0.933	–0.206	0.397
	KL	0.066	0.781	0.100	0.676	0.028	0.910
	HC	0.414	0.069	–0.149	0.531	–0.137	0.577
	AC	–0.311	0.183	–0.104	0.661	0.299	0.214
	PY	–0.020	0.935	0.125	0.598	–0.066	0.787

Note: Number of samples = 20. *r*, correlation coefficient; *p*, *p*-value; PY, kraft pulp yield; FL, fiber length; BD, basic density; HWE, hot-water extractives; AE, 1% NaOH extractives; OSE, organic-solvent extractives; KL, Klason lignin; HC, hemicellulose; AC, α-cellulose; KN, kappa number. Data of fiber length and basic density were cited from the previous papers.[12,13] Bold values indicate correlation coefficients with *p*-values less than 0.05

Among-provenance variations of chemical and kraft pulp properties of culms

Tables 4 to 6 show fixed- and random-effect parameter estimates of the model for explaining the among-provenance variations of three bamboo species. Table 7 shows the variance component ratio of the provenance in the model. Higher variance component ratios of the provenance were found in α-cellulose (59.9%) and pulp yield (48.4%) in *B. vulgaris*, hot-water (54.3%) and 1% NaOH (48.4%) extractives, Klason lignin (59.8%), holocellulose (53.2%), hemicelluloses (48.3%), and α-cellulose (41.5%) in *B. maculata*, and α-cellulose (46.9%) in *G. atter*.

Previously, we evaluated the among-provenance variations of anatomical, physical, and mechanical properties of bamboo culm in three species naturally grown on Lombok Island, Indonesia.[12,13] As a result, *G. atter* had large variance components in green moisture content, basic density, fiber area, modulus of elasticity, modulus of rupture, compressive strength, tensile Young's modulus, and tensile strength compared to the other two *Bambusa* species. In the *Bambusa* species, variance components of individual culm were larger than those of the provenance, suggesting that the properties differed between individuals within a provenance. In the present study, higher variance component ratios of the provenance with 40% and more were found in α-cellulose and pulp yield in *B. vulgaris*, hot-water and 1% NaOH extractives, Klason lignin, holocellulose, hemicelluloses, and α-cellulose in *B. maculata*, and α-cellulose in *G. atter* (Table 7). Although the formula differed between this study and the previous one, many chemical properties showed geographic variations. The samples used in the present study were collected from the natural population of all species at each site. Therefore, the among-provenance variations in chemical properties of culms might be related to the differences in the genetic backgrounds at the provenance level in each species. The obtained results suggested that provenance selections should be conducted when the culms of these bamboo species are utilized for chemical products.

Table 4
Parameter estimates, standard errors, *t*-values, and *p*-values of the model for among-provenance variations of *B. vulgaris*

Property	Fixed-effect parameter				Random-effect parameter estimates			
	Estimates	SE	*t*-value	*p*-value	Provenance I	Provenance II	Provenance III	Provenance IV
Hot-water extractives	–	–	–	–	–	–	–	–
1% NaOH extractives	24.544	0.836	29.360	< 0.001	–0.604	–0.011	0.431	0.184
Organic-solvent extractives	4.653	0.553	8.409	0.004	–0.797	–0.023	0.011	0.809
Ash	–	–	–	–	–	–	–	–
Klason lignin	26.385	0.424	62.190	< 0.001	0.476	0.487	–0.739	–0.225
Holocellulose	75.971	0.406	187.000	< 0.001	0.583	0.200	–0.323	–0.460
Hemicelluloses	26.200	0.409	64.030	< 0.001	–0.067	–0.662	0.724	0.004
α-Cellulose	49.771	0.705	70.570	< 0.001	0.952	1.139	–1.401	–0.690
β-Cellulose	5.089	0.630	8.080	0.004	–0.505	1.166	–0.326	–0.336
γ-Cellulose	21.111	0.970	21.760	< 0.001	0.528	–2.074	1.147	0.400
Kraft pulp yield	49.027	0.920	53.280	< 0.001	0.625	1.219	–2.211	0.367
Kappa number	–	–	–	–	–	–	–	–

Note: SE, standard error; –, model did not converge. Provenance I, II, III, and IV refer to Figure 1

Table 5
Parameter estimates, standard errors, *t*-value, and *p*-values of the model for among-provenance variations of *B. maculata*

Property	Fixed-effect parameter				Random-effect parameter estimates			
	Estimates	SE	*t*-value	*p*-value	Provenance I	Provenance II	Provenance III	Provenance IV
Hot-water extractives	8.886	0.952	9.334	0.003	0.393	–2.169	1.762	0.013
1% NaOH extractives	24.280	1.198	20.270	< 0.001	0.580	–2.482	2.251	–0.349
Organic-solvent extractives	5.426	0.477	11.370	0.001	0.118	–0.237	0.101	0.018
Ash	2.305	0.177	13.020	0.001	0.345	–0.105	–0.123	–0.118
Klason lignin	26.256	1.392	18.860	< 0.001	–0.243	3.446	–0.897	–2.307
Holocellulose	75.083	0.751	100.000	< 0.001	–1.268	–0.851	1.454	0.666
Hemicelluloses	25.266	0.850	29.720	< 0.001	–0.204	–0.819	2.036	–1.013
α-Cellulose	49.817	0.718	69.420	< 0.001	–0.970	–0.005	–0.595	1.571
β-Cellulose	7.109	0.515	13.820	0.001	–0.786	0.398	–0.004	0.392
γ-Cellulose	18.157	1.094	16.590	< 0.001	0.873	–1.251	1.792	–1.414
Kraft pulp yield	–	–	–	–	–	–	–	–
Kappa number	21.453	1.099	19.520	< 0.001	0.309	0.443	–0.501	–0.251

Note: SE, standard error; –, model did not converge. Provenance I, II, III, and IV refer to Figure 1

Table 6
Parameter estimates, standard errors, *t*-values, and *p*-values of the model for among-provenance variations of *G. atter*

Property	Fixed-effect parameter				Random-effect parameter estimates			
	Estimates	SE	*t*-value	*p*-value	Provenance I	Provenance II	Provenance III	Provenance IV
Hot-water extractives	–	–	–	–	–	–	–	–
1% NaOH extractives	–	–	–	–	–	–	–	–
Organic-solvent extractives	2.941	0.380	7.734	0.005	0.238	–0.178	–0.469	0.410
Ash	2.420	0.128	18.860	< 0.001	0.085	–0.182	0.121	–0.025
Klason lignin	25.571	0.326	78.480	< 0.001	–0.576	–0.084	0.334	0.325
Holocellulose	75.272	0.271	278.100	< 0.001	0.069	0.295	–0.099	–0.265
Hemicelluloses	23.384	0.727	32.150	< 0.001	–0.360	–0.738	–0.148	1.246
α-Cellulose	51.886	0.964	53.810	< 0.001	0.608	1.517	0.017	–2.142
β-Cellulose	6.298	0.434	14.500	0.001	0.845	–0.320	–0.332	–0.193
γ-Cellulose	17.086	0.909	18.800	< 0.001	–1.239	–0.487	0.171	1.555
Kraft pulp yield	52.326	1.174	44.590	< 0.001	1.104	–0.567	–0.030	–0.507
Kappa number	–	–	–	–	–	–	–	–

Note: SE, standard error; –, model did not converge. Provenance I, II, III, and IV refer to Figure 1

Table 7
Variance components of provenances and residual in the model of each property in three bamboo species

Property	*B. vulgaris*			*B. maculata*			*G. atter*		
	V_p	V_e	VC_p (%)	V_p	V_e	VC_p (%)	V_p	V_e	VC_p (%)
Hot-water extractives	–	–	–	3.103	2.614	54.3	–	–	–
1% NaOH extractives	0.738	10.287	6.7	4.728	5.046	48.4	–	–	–
Organic-solvent extractives	0.726	2.495	22.5	0.157	3.773	4.0	0.303	1.301	18.9
Ash	–	–	–	0.082	0.219	27.1	0.035	0.146	19.3
Klason lignin	0.505	1.077	31.9	6.832	4.599	59.8	0.281	0.680	29.2
Holocellulose	0.391	1.345	22.5	1.916	1.683	53.2	0.130	0.774	14.3
Hemicelluloses	0.465	1.027	31.2	2.381	2.550	48.3	1.260	4.044	23.8
α-Cellulose	1.755	1.174	59.9	1.607	2.264	41.5	3.000	3.391	46.9
β-Cellulose	0.985	3.010	24.7	0.573	2.431	19.1	0.493	1.236	28.5
γ-Cellulose	2.757	5.037	35.4	3.470	6.608	34.4	2.156	5.416	28.5
Kraft pulp yield	2.791	2.979	48.4	–	–	–	1.818	17.483	9.4
Kappa number	–	–	–	0.988	19.228	4.9	–	–	–

Note: V_p, variance component of the provenance; V_e, residual variance; –, model did not converge. VC_p (%) was calculated as the ratio of V_p to total variance ($V_p + V_e$)

CONCLUSION

In the present study, bamboo culms of three species (*B. vulgaris*, *B. maculata* and *G. atter*) were collected from four natural populations on Lombok Island, Indonesia. Chemical and kraft pulp properties were investigated using the collected samples. Compared with the previous research, the amounts of chemical components in the present study were in the range of those results. The mean kraft pulp yield and kappa number ranged from 49.0 to 52.3% and 18.7 to 22.3, respectively. Significant differences among the three species were found in pulp yield and kappa number. Based on the correlation analysis of measured properties, the relationships between kraft pulp properties and amounts of chemical components might differ among bamboo species. Judging from the results of mixed-effect modeling, the chemical properties of three bamboo species have among-provenance variations. Based on the results, it is considered that the kraft pulp properties are similar to those produced from wood of tropical fast-growing tree species, indicating that the culm resources of the three bamboo species can be utilized as raw materials of kraft pulp instead of wood. In addition, *G. atter* is the most suitable species for kraft pulp compared to the other *Bambusa* species. Furthermore, when bamboo culm is collected from natural populations, the provenance selection is essential to utilize the culm of three bamboo species for chemical products.

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