# Morphological and Chemical Characterization of Green Bamboo (*Dendrocalamopsis oldhami* (Munro) Keng f.) for Dissolving Pulp Production

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With the sustained growth of dissolving pulp demand all over the world, the search for alternative bamboo materials has come into focus in China due to the shortage of wood and the abundance of bamboo resources. In this study, to obtain updated information concerning green bamboo growing in southeastern China and to develop its processing technologies for dissolving pulp, the fiber morphology, chemical composition, elemental composition, degree of polymerization (DP) of cellulose, and crystallinity index (CrI) of cellulose were investigated. The experimental results show that green bamboo has potential for use as dissolving pulp because it has a lower Runkel ratio and fines content than moso bamboo, and a much lower lignin content and similar α-cellulose and hemicellulose contents compared to softwoods and hardwoods. Compared to the cortex and culm, the node had the shortest fibers and more than 30% of fines, the highest content of extractives and lignin, and the lowest *α*-cellulose content. As a result, a de-knotting operation prior to cooking can contribute to the production of high-grade dissolving pulp. The DP and CrI of cellulose from the node were much lower than that of cellulose from the culm and cortex. Moreover, green bamboo had the high content of ash, primarily distributed in the cortex. The concentration of Si was 4487 ppm in the cortex, nearly five times higher than that in the culm and node.

*Keywords: Green bamboo; Morphology; Chemical composition; Dissolving pulp*

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## INTRODUCTION

Dissolving pulp is an important starting material for the production of cellulose derivatives and regenerated cellulose (Wan Rosli *et al*. 2004). The traditional two major resources for the production of dissolving pulp are cotton linters (soda pulping) and wood pulp (pre-hydrolysis kraft and acid sulfite pulping processes) (Barba *et al*. 2002). With the increasing demand for and cost of pulpwood, new alternative raw materials for the production of dissolving pulp have been investigated (Behin and Zeyghami 2009). Non-wood raw material is one of the alternatives and is especially popular in China, where there is a fiber shortage for the pulp and paper industry. Bamboo is a very promising alternative non-wood raw material and has been already used extensively in China for the production of paper-grade and dissolving pulp due to its unique properties, such as a high growth rate, low resource cost, long or semi-long fibers, and similar α-cellulose content compared to most trees (Mân Vu *et al.* 2004; Runge *et al*. 2012).

Dissolving pulp is a low-yield chemically refined bleached pulp (30 to 35%) with a high cellulose content (95 to 98%), a low hemicelluloses content (2 to 4%), and traces of residual lignin, extractives, and minerals (< 0.05%) (Christov *et al.* 1998; Sixta 2006). A low degree of polymerization and a uniform molecular weight distribution of dissolving pulp are also desired for the production of viscose. Bamboo materials are subjected to pulping, bleaching, or even special treatments to purify the fibers to prepare dissolving pulp (Ma *et al.* 2012). The dissolving bamboo pulp quality depends on not only the pulp and purification processing but also the properties of the raw bamboo material, such as the morphology and chemical composition. Chemical composition plays an important role in producing high-grade dissolving pulp. The high content of hemicelluloses has a negative effect on the viscose filterability, the cellulose xanthanation process, and the end product quality (Gübitz *et al.* 1997). The fiber morphology is another important factor for the reactivity of dissolving pulp that can affect the accessibility or reactivity of cellulose to solvents or reagents (Klemm *et al.* 1998; Sixta 2006; Hult *et al*. 2011). The compact fibrillar structure of the cellulose gives rise to a poor reactivity (Ibarra *et al*. 2010). Additionally, the presence of trace elements, such as silicon (Si), calcium (Ca), iron (Fe), and manganese (Mn), should also be carefully considered because they are detrimental to the production of dissolving pulp (Sixta 2006; Xia *et al.* 2013; Loureiro *et al*. 2012).

Green bamboo (*Dendrocalamopsis oldhami* (Munro) Keng f.) is widely planted in southeastern China, especially in Fujian Province, due to China's unique topography and climatic conditions. Because plant development and growth characteristics are affected by environmental factors, it is important to study the characteristics of green bamboo to evaluate their suitability as an alternative raw material for the production of dissolving pulp. Moreover, as a feedstock for the production of dissolving pulp, it is very necessary to have updated information on green bamboo related to the selection and optimization of processes and technologies and the quality estimation of the end product. The authors have prepared green bamboo dissolving pulp by prehydrolysis and kraft pulping. The kinetics and mechanism of pentosan dissolution during the hydrolysis process were studied, and the kinetics of kraft delignification of hydrolyzed bamboo was investigated (Ma *et al.* 2011, 2012b). The purpose of this research is to further explore the chemical composition, morphological performance, and cellulose characteristics of green bamboo for developing processing technologies to obtain high-quality dissolving pulp.

## EXPERIMENTAL

### Materials

Two-year-old green bamboo (*Dendrocalamopsis oldhami* (Munro) Keng f.), moso bamboo (*Phyllostachys edulis*) materials were respectively obtained from Nanan Forest Farm and Huaan Botanic Garden in Fujian, China. Bamboo culm (without the cortex and node), cortex, and node were collected. Parts of them were used for morphological analysis, and the other parts were pulverized into powder (passed through a 40-mesh and retained at a 60-mesh sieve) for chemical analysis. All reagents used in the experiment were of analytical grade and used as received.

## Methods

*Fiber separation and morphology analysis*

The sample chips were split into smaller 1 mm × 2 mm × 30 mm sticks. The air entrapped in the sticks was excluded by heating the sticks with boiling water several times until the sticks were fully saturated, and then the degassed sticks were immersed in a mixture of acetic acid and 30% $H_2O_2$ at a ratio of 1:1 (v/v) at 60 $^oC$ for about 48 h until the fibers turned white and were totally separated. The separated fibers were thoroughly washed and then used for morphological analysis. The images and morphological parameters of bamboo fibers, namely length, diameter, wall thickness, lumen diameter, and fines content (% in area), were determined using a Hi-Res Fiber Quality Analyzer (OpTest, Canada) and Olympus BX51 light microscopy (Olympus, Japan).

Three derived values were also calculated according to the fiber dimensions: slenderness ratio (fiber length/fiber diameter), flexibility ratio [(fiber lumen diameter/fiber diameter)×100], and Runkel ratio [(2×fiber cell wall thickness)/fiber lumen diameter] (Saikia *et al*. 1997; Ogbonnaya *et al*. 1997). The values were then analyzed to assess the suitability of green bamboo for dissolving pulp production.

*Extractives, holocellulose, and lignin content analysis*

The benzene-alcohol extractives content of the samples was measured according to TAPPI method T204 cm-97.

Holocellulose was separated by sodium chlorite/acetic acid delignification (Wise *et al*. 1946; Hubbell and Ragauskas 2010). In brief, a sawdust sample (2.00 g dry weight) was first extracted with a mixture of benzene and alcohol (2:1, v/v) for 8 h. The extractives-free sawdust was then placed in a Kapak sealing pouch with deionized water (65.00 mL), sodium chlorite (0.60 g), and glacial acetic acid (0.50 mL). The plastic pouch was sealed and placed in a reciprocating water bath at 75 $^oC$ for 1 h. After 1 h, another batch of sodium chlorite and glacial acetic acid was added, and the plastic bag was resealed and placed back in the reciprocating water bath at 75 $^oC$ for another hour. After a total of 4 h and four batches of sodium chlorite and glacial acetic acid, the sample was removed from the bath, and the solid residue (holocellulose) was filtered through a sintered-glass filter and washed thoroughly with deionized water until the filtrate was neutral. The final content of holocellulose was calculated by subtracting the ash content due to the high ash content in the green bamboo.

The Klason lignin was determined by TAPPI standard method T222 om-06; the hydrolysis filtrate was further used for determination of acid-soluble lignin content according to NREL/TP-510-42617.

*Metal element analysis*

Before analysis, 0.5 g of dried sample (green bamboo powder) was put into the digestion vessel of a microwave oven and digested with 7 mL of ultrapure nitric acid (65%, m/m, Merck, German) and 3 mL of hydrogen peroxide (30%, m/m, Merck, German). A programmable 1200-W microwave (MARS 5, CEM Corp., Matthews, NC, USA) with a rotor for 14 Teflon-lined vessels served as the closed vessel digestion system. Pressure and temperature profiles in the vessels were monitored on an external computer. The microwave digestion conditions are shown in Table 1. The resulting solutions were cooled to room temperature and filled up to 50 mL with ultrapure deionized water (18 MΩ/cm, Milli-Q Element system, Millipore, Bedford, MA, USA).

**Table 1.** Microwave Digestion Conditions

| Program step | Power (W) | Heating rate (°C/s) | Temperature (°C) | Time (min) |
|---|---|---|---|---|
| 1 | 1600 | 5 | 120 | 3 |
| 2 | 1600 | 3 | 150 | 3 |
| 3 | 1600 | 3 | 180 | 20 |

ICP-MS analysis was performed on the equipment (Agilent 7500e, Agilent, Foster, CA, USA). The operating conditions were optimized and are shown in Table 2. Blanks were prepared for each batch of samples. All experiments were performed in triplicate.

**Table 2.** Instrumental Operating Conditions of ICP-MS System

| ICP-MS system parameter | Operating condition |
|---|---|
| RF power (W) | 1550 |
| Cooling gas flow (L/min) | 15.0 |
| Auxiliary gas flow (L/min) | 1.0 |
| Compensating gas flow (L/min) | 0.25 |
| Sampling depth (mm) | 8.0 |
| Analytical model | Quantitative analysis |
| Oxide ($CeO^+/Ce^+$) | <0.5% |
| Double charge ($Ce^{2+}/Ce^+$) | <3% |
| Spray chamber temperature (°C) | 2 |
| Sample uptake rate(mL/min) | 0.4 |
| Sampling cone | Nickel, 1.0-mm orifice |
| Skimmer cone | Nickel, 0.6-mm orifice |
| Integration time (s) | 0.1 |
| Number of repetitions/sample | 3 |

*Ash and silicon (Si) analysis*

The ash content was determined by TAPPI standard method T211 om-07. $SiO_2$ content was determined by treating the resultant ash with HCl (hydrochloric acid) to solubilize and remove the silica, while the Si content was calculated using the $SiO_2$ content and its proportion by mass. In brief, 10 mL of 4 N HCl was added to the resultant ash in the crucible and the crucible was heated in a boiling water bath for 10 min to evaporate the solution. The resultant ash was treated again with 10 mL of 4 N HCl, and then the crucible loaded with the ash was heated at 105 °C for 1 h. After the ash was cooled to room temperature, 2 mL of 4 N HCl was added to the crucible, and the ash was transferred to a dried and weighed sintered glass crucible (G4) and washed with 100 mL of deionized water. The residue in the crucible was washed again several times with hot deionized water until the filtrate was free of Cl ($AgNO_3$ was used to indicate the filtrate). The crucible with the residue was dried in an oven at 105 °C for 2 h to obtain the constant weight of $SiO_2$. $SiO_2$ content was calculated based on the percentage of $SiO_2$ mass to the oven-dry sample mass. Finally, the content of Si element was calculated by multiplying the content of $SiO_2$ and the relative molecular mass ratio (0.467).

*Isolation of α-cellulose*

*α*-cellulose is defined as the residue of holocellulose insoluble in a 17.5 wt% NaOH solution, which is considered to represent the undamaged higher molecular weight of cellulose in a wood or biomass sample. The *α*-cellulose was isolated from holocellulose by extraction with NaOH solution. In brief, 5 g of holocellulose was added

to 100 mL of NaOH solution (17.5 wt%) at 25 ºC for a 30-min incubating period. Then, 100 mL of deionized water was added to the NaOH solution. The extraction was continued with 8.75% NaOH solution at 25 ºC for an additional 30 min. The solution was filtered repeatedly three times to obtain the residue, which was then filtered and washed three times with 300 mL of deionized water (each 100 mL). Then, 15 mL of 10 wt% acetic acid solution was added to the residue for 5 min. After that, the residue was filtered and washed with hot deionized water (~ 500 mL) several times until the filtrate was neutral, and the residue was dried at 105 ºC. Finally, the amount of $\alpha$-cellulose was determined gravimetrically, and the amount of hemicellulose was calculated by subtracting $\alpha$-cellulose from holocellulose.

*DP determination of cellulose*

First, the intrinsic viscosity of the samples ($\alpha$-cellulose) was measured at 25 ºC with a capillary-tube viscometer using cuproethylenediamine as a solvent according to the Martin equation (Scandinavian standard SCAN-CM 15:99 and ISO 5351:2012). Then, the DP value of cellulose was calculated by applying the following formula: $DP^{0.905} = 0.75[\eta]$ (Sihtola *et al.* 1963).

*Determination of CrI of cellulose*

X-ray diffraction data were obtained using a Japan MiniFlex2 instrument with powder samples. Ni-filtered Cu-Kα radiation generated at a voltage of 30 kV and current of 15 mA was utilized. The scanning angle range was 5° to 45° with a scan speed of 5°/min. The crystallinity index was calculated from the ratio of the height of the 002 peak (I002) and the height of the minimum (IAM) according to the peak height method developed by Segal and co-workers (Segal *et al.* 1959).

## RESULTS AND DISCUSSION

### Morphological Characterization

The importance of plant material's fiber dimensions and their derived values (slenderness ratio, flexibility coefficient, and Runkel ratio) on pulp and paper mechanical strength is well documented (Kellogg and Thykeson 1975; Seth and Page 1988; Horn and Setterholm 1990; Saikia *et al.* 1997; Madakadze *et al.* 1999). Fiber characteristics such as fiber length, fiber diameter, lumen diameter, cell-wall thickness, and their derived values play an important role in estimating the quality of pulp. The fiber dimensions of green bamboo and moso bamboo and their derived values are shown in Table 3. The length, diameter, and thickness of green bamboo fibers were comparable to those of moso bamboo fibers, whereas the average lumen diameter of green bamboo fibers was much larger than that of moso bamboo fibers. As a result, the Runkel ratio of green bamboo fibers was less than that of moso bamboo fibers, although the slenderness ratios were quite similar for both types of bamboo. Therefore, pulp made from green bamboo was expected to have increased mechanical strength (Neto *et al*. 1996; Oluwafemi and Sotannde 2007). Additionally, it is worth noting that the fines of green bamboo accounted for 24.4% of its total fibrous part, which was less than that of moso bamboo (29.5%). This indicated that green bamboo has better potential for papermaking than moso bamboo

because fines have a significantly negative effect on pulp mechanical strength (Horn and Setterholm 1990; Shatalov and Pereira 2002).

**Table 3.** Fiber Morphology Comparison between Green Bamboo and Moso Bamboo

| Bamboo material | Fiber length (L) (mm) | Fiber diameter (D) (μm) | Fiber wall thickness (W) (μm) | Fiber lumen diameter (l) (μm) | Slenderness ratio (L/D) | Runkel ratio (2W/l) | Flexibility ratio (l/D) | Fines (%) |
|---|---|---|---|---|---|---|---|---|
| Green bamboo | 2.19 | 13.83 | 5.17 | 3.49 | 158.3 | 2.96 | 0.25 | 24.4 |
| Moso bamboo | 2.23 | 13.93 | 5.71 | 2.52 | 160.1 | 4.53 | 0.18 | 29.5 |

Figure 1 shows images of the three samples from the culm, cortex, and node of green bamboo. The morphology of both culm and cortex samples were almost the same, whereas quantities of parenchyma cells were present on the node sample. Thin-wall parenchyma cells could plug the sheet, reducing paper machine drainage. With mild mechanical action, these cells were crushed, further reducing the ability to remove water from the sheet.

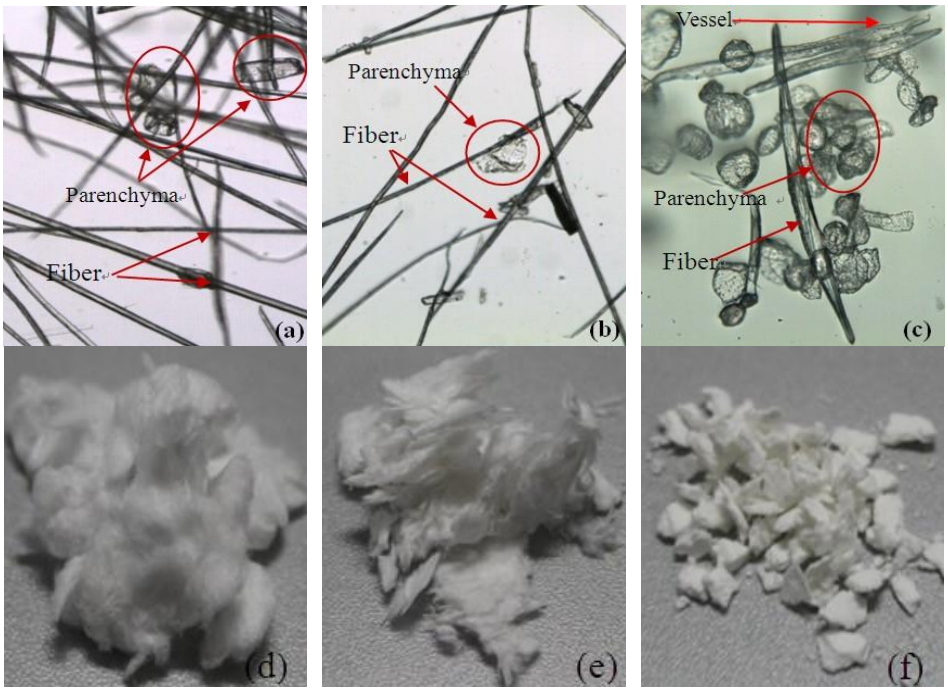


**Fig. 1.** Fiber morphology of bamboo samples (a, d-culm; b, e-cortex; c, f-node)

The data in Table 4 show the morphological characteristics of fibers from the culm, cortex, and node. The fibers from the cortex had the longest average length, 2.58 mm, followed by those from the culm and node. Notably, the length of the node was only 0.66 mm, about 28% that of fibers from the culm. Similarly, the fibers from different parts of green bamboo had different diameters: 12.31 μm for the culm, 10.44 μm for the cortex, and 29.90 μm for the node. The fibers from the cortex had the thinnest average diameter, with an L/D ratio of 247.1, and the fibers from the node had the largest average

diameter, with an L/D ration of 22.1. With shorter fiber lengths and wider fiber diameters, 30.5% of fibers from the node are considered fines, whereas the fines contents of the cortex and culm samples were significantly lower, especially for fiber from the culm. The shorter and thinner fibers from the node yielded a finer, more flour-like pulp, which is shown in Fig. 1. The presence of the node significantly decreased the average length of the fibers, which could lead to poor drainage and pulp properties. To produce high-grade pulp, de-knotting was necessary prior to cooking using suitable screening techniques, which can increase costs.

**Table 4.** Fiber Morphology of the Samples

| Green bamboo | Fiber length (L) (mm) | Fiber diameter (D) (μm) | Fiber wall thickness (W) (μm) | Fiber lumen diameter (l) (μm) | Slenderness ratio (L/D) | Runkel ratio (2W/l) | Flexibility ratio (l/D) | Fines (%) |
|---|---|---|---|---|---|---|---|---|
| Culm* | 2.39 | 12.31 | 4.33 | 3.65 | 194.2 | 2.37 | 0.30 | 0.6 |
| Cortex | 2.58 | 10.44 | 3.61 | 3.23 | 247.1 | 2.24 | 0.31 | 1.5 |
| Node | 0.66 | 29.90 | 12.44 | 5.02 | 22.1 | 4.96 | 0.17 | 30.5 |

*Note: Culm part excluding cortex

## Chemical Composition

Similar to other lignocellulosic materials, the primary chemical components of green bamboo are cellulose, hemicellulose, and lignin. The chemical compositions of the different morphological parts of green bamboo are listed in Table 5. In comparison with the traditional raw materials used in the pulp and papermaking industry, the content of holocellulose in green bamboo was much lower than in softwoods, higher than in straw, and still similar to those of hardwoods, except for the higher ash content (Cai and Tao 2007; Gong 2007; Liu *et al.* 2003). The α-cellulose content of green bamboo culm was 45%, much higher than that of grasses but comparable with that of softwood. The α-cellulose content of Masson pine is 44.28% (Cai and Tao 2007), which could be characterized as promising for manufacturing dissolving pulp from a chemical composition point of view.

The lignin content in green bamboo was much lower than that of softwoods and hardwoods (Cai and Tao 2007; Gong 2007), which indicated a more efficient delignification as compared to wood at given cooking conditions. In practice, this means that green bamboo would need milder pulping conditions (lower temperatures and chemical charges) than softwoods and hardwoods to reach a satisfactory kappa number, which can reduce energy and chemical consumption.

The hemicellulose content needs to be very low in high-purity dissolving pulp because hemicellulose may cause severe difficulties during utilization of the dissolving pulp for production of cellulose derivatives. Compared to woods, bamboos generally have higher hemicellulose content and lower lignin content. However, the hemicellulose content of green bamboo was approximately equal to that of wood (Gong 2007), which is beneficial for the manufacture of dissolving pulp due to the removal of hemicellulose with milder pre-hydrolysis conditions.

In addition, the alcohol-benzene solubles in green bamboo (3.3%~3.9%) are higher than those in wood, such as poplar with the benzene-alcohol extractive content of 2.14% (Gong 2007), but lower than that in grasses, such as rice straw with the benzene-alcohol extractive content of 7.45% (Liu *et al.* 2003). This indicated that green bamboo

contained more substances like waxes, fats, resins, phytosterols, non-volatile hydrocarbons, low-molecular weight carbohydrates, salts, and other water-soluble substances. A higher extractives content is quite challenging for dissolving pulp production. Extractives may be converted into pitch, which can adversely affect the runnability of process equipment by choking the Fourdrinier wire. Therefore, more attention should be given to the extractives in green bamboo during the manufacture of dissolving pulp.

The chemical composition of green bamboo differed among the morphological parts. Table 5 shows that the holocellulose and *α*-cellulose content was highest in the cortex, followed by the culm and node. With respect to the composition of the node, the lignin content was about 25.2%, which was higher than that of the culm and cortex, while the *α*-cellulose content was much lower than that of the culm and cortex. The extractives of the culm, cortex, and node samples had little difference; all accounted for about 3.90% of the gross mass. The experimental results indicated that the distribution of bamboo cellulose and lignin differed from that of wood. The woods had commonly the lowest holocellulose and cellulose content, but the highest Klason lignin and ash contents in the outer bark (Usta and Kara 1997). Consequently, the nodes of green bamboo should be removed prior to the pulping process so that the highest purity of dissolving pulp can be obtained.

**Table 5.** Chemical Composition of Green Bamboo Samples

| Green bamboo | Extractives (%) | Holocellulose (%) | Lignin (%) | | α-cellulose (%) | Hemicellulose[c] (%) | Ash (%) | Total (%) |
|---|---|---|---|---|---|---|---|---|
| | | | AISL[a] | ASL[b] | | | | |
| Culm | 3.9±0.1 | 71.1±0.3 | 20.9±0.1 | 2.2±0.2 | 45.0±0.1 | 26.1 | 1.5±0.2 | 99.6 |
| Cortex | 3.3±0.2 | 72.2±0.2 | 23.5±0.2 | 2.1±0.2 | 47.1±0.2 | 25.1 | 2.1±0.2 | 103.3 |
| Node | 3.9±0.1 | 68.6±0.1 | 25.2±0.3 | 3.1±0.1 | 34.1±0.1 | 34.5 | 1.9±0.1 | 102.7 |

[a] AISL - acid insoluble lignin; [b] ASL - acid soluble lignin; [c] Hemicellulose: the hemicellulose content was calculated by subtracting the amount of α-cellulose from the holocellulose content.

Understanding the cellulose characteristics of bamboo is fundamental to its use as a feedstock. The proper DP of cellulose and the uniform molecular weight distribution are important for viscose production. There are many reports confirming that the DP of dissolving pulp is a significant property in the production of rayon fibers. The strength characteristics of rayon fibers are reduced with a decrease in the DP value of dissolving pulp (Sixta 2006). Consequently, the prehydrolysis, cooking, and bleaching conditions should be optimized to obtain a relatively high DP of cellulose. Table 6 shows that the DP of cellulose in the node of green bamboo was much lower than those of celluloses in the culm and cortex. As a result, the DP value of dissolving pulp from the node was particularly low, which represented the weakest part in the fiber and significantly reduced the strength characteristics of rayon fibers. Removing the nodes during the preparation of green bamboo chips would be beneficial for the production of dissolving pulp.

Many cellulosic materials consist of crystalline and amorphous regions in different proportions, and these crystalline and amorphous regions affect the accessibility and chemical reactivity of the dissolving pulp (Ciolacu *et al.* 2011). Moreover, the crystallinity of cellulosic materials is affected by cooking and bleaching conditions, such as chemical agents, temperature, and pressure (Gümüskaya *et al*. 2003; Carrasco *et al*. 1994). Table 6 shows that the highest crystallinity index of cellulose was in the culm, followed by the cortex, while the lowest crystallinity index was for the node. As a result,

the cellulose in the node might be more easily degraded during the preparation of dissolving pulp, leading to a lower yield of dissolving pulp and poor strength properties of rayon fibers.

**Table 6.** DP and Crystallinity Index of Green Bamboo Cellulose

| Green bamboo | Culm | Cortex | Node |
|---|---|---|---|
| CrI /%* | 59.8 | 59.0 | 50.1 |
| DP | 1395 | 1406 | 932 |

*For lignocellulosic materials, lignin and hemicelluloses may affect the accuracy of the XRD value (Andersson *et al.* 2003); the data are only relative values.

## Ash Constituents

It is apparent from Table 5 that green bamboo had the highest ash content in the cortex, followed by the node and culm, at about 2.1%, 1.9%, and 1.5%, respectively. The ash distribution is consistent with the results from Usta's study (Usta and Kara 1997). The inorganic elements in the green bamboo are shown in Table 7. Si was the main inorganic element in the green bamboo samples, and its concentration was several times higher than that of other metal elements. The concentration of Si was up to 4487 ppm in the cortex, nearly 5 times higher than that in the culm and node. In addition to Si, there were other metal elements present in the bamboo material, such as Mg, Ca, Mn, Al, Cu, and Na, which would be detrimental to the subsequent bleaching or viscose production process (a gradual clogging of the spinnerets). It is well known that transition metals such as Mn, Fe, and Cu have negative effects on the bleaching selectivity and pulp bleachability in the hydrogen peroxide bleaching stage (Loureiro *et al*. 2012). It has also been reported that some metals present in cotton may contribute to problems in yarn manufacturing, bleaching and dyeing, and processing quality (Rezić and Steffan 2007). Briefly, the ash constituents had a detrimental effect on the processing and quality of dissolving pulp. Consequently, the negative effects of ash should be taken into full consideration in process optimization.

Although residual ash in a dissolving pulp is considered a contaminant for the preparation of cellulose derivatives, most of the harmful ash components are not distributed homogeneously in the pulp, but are present in certain cell fractions, particularly in the parenchyma cells (Sixta 2006). Therefore, the pressure screening of unbleached pulp and centrifugal cleaning after bleaching can be utilized to reduce the amount of harmful ash components. Additionally, prehydrolysis can also remove ash from raw materials (Wan Rosli *et al*. 2003).

**Table 7.** Metal and Si Contents of Green Bamboo

| Green bamboo | Mg (ppm) | Ca (ppm) | Mn (ppm) | Fe (ppm) | Al (ppm) | Na (ppm) | Cu (ppm) | Si (ppm) | Total (ppm) |
|---|---|---|---|---|---|---|---|---|---|
| Culm | 466.6 | 419.0 | 50.0 | 8.0 | 5.9 | 9.0 | 1.8 | 810 | 1770 |
| Cortex | 234.3 | 141.4 | 185.1 | 120.2 | 60.1 | 27.4 | 2.6 | 4487 | 5258 |
| Node | 317.5 | 278.7 | 37.7 | 31.3 | 18.8 | 12.1 | 4.9 | 1543 | 2244 |

1 ppm=1 mg/kg

## CONCLUSIONS

1. Green bamboo has better potential for the manufacture of paper-grade and dissolving pulp than moso bamboo due to the lower Runkel ratio and fines content. Compared to the cortex and culm, the node sample had the shortest fibers and more than 30% of fines. De-knotting of green bamboo could produce higher grade dissolving pulp prior to cooking using suitable screening technologies.

2. Compared to softwoods and hardwoods, green bamboo has much lower lignin content and similar α-cellulose and hemicellulose content, which could be characterized as promising for dissolving pulp manufacture. However, green bamboo has a high content of extractives, which could be challenging for dissolving pulp production. In addition, the node of green bamboo has a higher lignin content and much lower *α*-cellulose content than the culm and cortex.

3. The DP value of cellulose in the node of green bamboo was found to have a much lower than that of cellulose in the culm and cortex, representing the weakest part in the fiber and significantly reducing the strength characteristics of rayon fibers. The lowest crystallinity index of cellulose was from the node. The cellulose in the node might be more easily degraded during the preparation of dissolving pulp, leading to a lower yield of dissolving pulp and poor strength properties of rayon fibers.

4. Green bamboo has a high content of ash, which was mainly distributed in the cortex. Si was the main inorganic element in the green bamboo, with a concentration several times higher than that of other metal elements. Moreover, the concentration of Si was 4487 ppm in the cortex, nearly 5 times higher than that in the culm and node.

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