Variations in Fiber Morphology and Chemical Components of *Dendrocalamus giganteus*

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Abstract

The fiber and chemical properties of *Dendrocalamus giganteus* at three ages from three different sites in China were investigated. For samples from all sites, the fibers in the middle internodes of culms were longer than those of other internodes. A similar trend was also observed within one internode. The fiber achieved its maximum length after 1 year, but the maximum length differed with site. The chemical composition and fiber characteristics also varied with height and site. Bamboo culms at the age of 3 years were suitable for utilization purposes, and the bamboos of Cangyuan provenance were the best for pulping and processing. They were also more suitable for popularization as a timber-yielding type owing to having the longest fibers and the lowest ratio of wall thickness to lumen diameter, the lowest SiO_2 and lignin contents, and the highest holocellulose content.

Bamboo is one of the most important nontimber forest products and one of the most important agricultural nonannual plants in the world (Lybeer et al. 2006). The bamboo culm of various species is widely used for many economic purposes, and therefore durability and other properties are important (Alvin and Murphy 1988). The suitability of bamboo culms for large-scale utilization as alternative and supplementary raw materials for the wood processing industry in Europe has been clearly demonstrated (Van Acker et al. 2000). Bamboo is the fastest-growing plant in the world, and this provides a benefit in terms of utilization of its fiber and chemical constituents. As a monocot, bamboos usually grow to their full height and diameter in 3 to 4 months. With the maturation of bamboo culms, fiber cells will complete their growth in length and diameter, but fiber walls will still continue to thicken and form a polylamellate structure by secondary thickening year after year (Wang et al. 2011). The chemical constituents of bamboo culms vary with their growth, development, and maturation stages. Some anatomical and chemical properties of bamboo culms have been reported by many researchers, involving various species, ages, and locations (Grosser and Liese 1971, Abd Latif et al. 1990, Jassen 1991, Abd Latif 1993, Norul Hisham et al. 2006, Li et al. 2007, Wang et al. 2011). In China, the chemical properties of many bamboo species have been analyzed, including *Phyllostachys edulis* (or *P. pubescens*), *P. glauca*, *P. nigra*, *P. heteroclada*, *P. bambusoides*, *P. praecox*, *Bambusa chungii* (*Lingnannia chungii*), *B. textilis*, *B. pervariabilis*, *B. distegia*, *B. wenchouensis*, *Dendrocalamus peculiaris*, and *D. latiflorus* (Wu et al. 1995, Lin et al. 2000, Zhang et al. 2002, Su et al. 2005, Yang et al. 2007). However, few bamboo species have been studied for the relationship between the geographical sites and the chemical and fiber properties of culms, except for *B. chungii* and *Fargesia yunnanensis* (Yang et al. 2009, Wang et al. 2011).

Dendrocalamus giganteus is distributed mostly in South Asian countries, such as India, Bhutan, Nepal, Thailand, and

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Forest Prod. J. 66(5/6):319–325.
doi:10.13073/FPJ-D-15-00043

Burma (Chongtham et al. 2011, Singhal et al. 2013). In China, *D. giganteus* is abundantly found in the southern and southwestern parts of Yunnan Province. Longchuan, Cangyuan, and Simao counties were the main distribution areas of this species in Yunnan Province (Fig. 1). It has an important economic role in local wood consumption. Several studies have also been performed to analyze its fiber and chemical properties (Wang et al. 2008, Zhao et al. 2011, Cheng et al. 2015), but almost all these studies did not involve the effects of height, age, and site on the wood properties. Wang et al. (2009) reported that the growth characteristics are variable among the geographical provenances, while the variation in fiber morphology and chemical composition with site has not been elucidated. They considered that choosing the best provenance is important for popularizing a bamboo species in managing bamboo forests. Hubert and Cundall (2006) also considered that planting the incorrect provenance can result in the grower's struggling with establishment over many years and, in some cases, total failure of the planting stock. Many bamboo species have been planted over recent decades with relatively little attention being paid to the provenance or origin of the seed used in China, such as moso bamboo (*P. edulis*), *Dendrocalamus brandisii*, *D. latiflorus*, and *D. giganteus*. Therefore, the objective of this study was to determine the effects of age, height (position within culm), and geographical sites on the fiber and chemical properties of *D. giganteus*. This is to supply fundamental information for utilization and to select the most suitable provenance for popularization as timber-purpose bamboo.

Materials and Methods

Materials

The *D. giganteus* culms were collected from three geographical sites in China: Longchuan County (24°12′N, 90°48′E; 940 m above sea level [asl]), Cangyuan County (23°08′N, 99°15′E; 1,340 m asl), and Simao County (22°44′N, 101°02′E; 1,400 m asl) (Fig. 1). The three sites are located in a moist subtropical climate, and weather conditions were collected by the authors and are shown in Table 1. The culm age was determined by monitoring the growth starting from new shoots that emerged from the ground (Norul Hisham et al. 2006). Five culms with similar diameters ranging from 5.5 to 7.5 cm for each age class (1, 2, and 3 yr) were felled. Three internodes were selected from each culm—internodes 3, 8, and 17—from the bottom, middle, and top part of the culm, respectively. All internode samples from different sites were cut into small strips measuring 2 by 2 by 50 mm. One-third of these strips from all internode samples were used for the determination of fiber morphology, and the others were used for the determination of chemical components.

An additional five 3-year-old culms from Longchuan County were selected for determination of variation in fiber morphology (fiber length, lumen diameter, and tangential diameter) within one internode length. Longchuan County was chosen because the popularization and processing of *D. giganteus* were the best in the local region. Only internode 8 (30 to 40 cm) was used because it was one of the longest internodes in the culms. This middle internode was cut into 10 equal circular cross sections (number 1 of supranodal ridge to number 10 of sheath scar, each 3 to 4 cm long, as shown in Fig. 2). All sections were cut into small strips measuring 2 by 2 by 50 mm (Fig. 2), and one-third of these strips of each section were macerated for the determination of fiber morphology.

Determination of fiber morphology

The strips were macerated in Jeffrey's solution, containing 10 percent aqueous nitric acid and 10 percent aqueous chromic acid (Jeffrey 1917), and heated at 40°C for 72 to 96 hours. A total of 150 fibers from the strips of each sample were measured for length, tangential diameter, wall thickness, and lumen diameter (Norul Hisham et al. 2006).

Determination of chemical components

The remaining two-thirds of the strips from each internode were oven-dried at 60°C for 24 hours and then ground with a Wiley mill, followed by filtering with No. 40

Figure 1.—The three sampling sites of Dendrocalamus giganteus *(▲) and the major distribution regions of this bamboo species.*

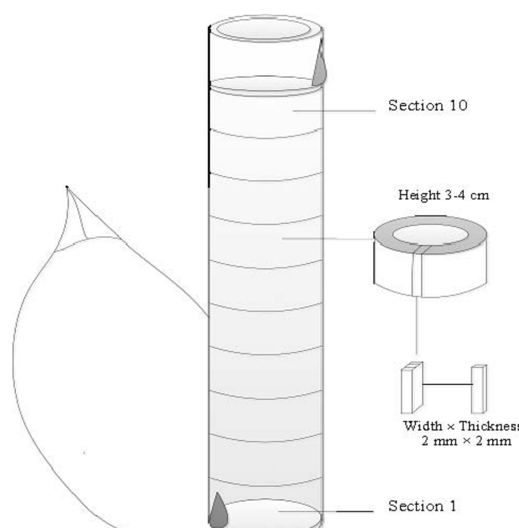

Figure 2.—The sampling schematic diagram of the middle part (internode 8) from the 3-year-old culms of Longchuan provenance. All 10 circular transverse sections were cut into small strips, 3 to 4 cm long, 2 mm wide, and 2 mm thick.

Table 1.—Climate data of three sites in China where samples were collected.

Site	Temperature (°C)				Annual precipitation (mm)	Annual sunshine (h)
	Annual avg.	Minimum	Maximum	Accumulated		
Longchuan	21.0	−1.3	34.6	7,500.0	2,200.0	2,115.0
Simao	17.8	3.0	33.0	7,200.0	1,524.4	2,000.0
Cangyuan	18.9	0.7	34.2	7,081.0	1,595.0	2,368.8

and No. 60 mesh sieves. The residues on the No. 60 mesh sieve were used for subsequent chemical analysis. The alcohol-toluene extractives, holocellulose, lignin, SiO_2, and ash contents were analyzed according to the Chinese National Standard testing methods GB/T 10741 (Standardization Administration of China [SAC] 1989), GB/T 2677.10 (SAC 1996), GB/T 2677.8 (SAC 1994), GB/T 7978 (SAC 1987), and GB/T 2677.3 (SAC 1993), respectively. The determination of each index was conducted in triplicate for each culm sample. Finally, the mean value of each index was calculated based on 15 samples from five representative culms in each age class.

The data from the experiments were statistically analyzed with analysis of variance and the least significant difference method. The sampling schematic diagram of the middle part (internode 8) from the 3-year-old culms (Fig. 2) is presented using Microsoft Visio 2010.

Results and Discussion

Variation in fiber morphology

Fiber dimensions.—The averages of fiber length, tangential diameter, length/tangential diameter (L/T) ratio, lumen diameter, wall thickness, and wall thickness/lumen diameter (W/Lu) ratio ranged from 0.82 to 6.42 mm, from 3.38 to 31.46 μm, from 52.11 to 680.33, from 1.30 to 22.88 μm, from 0.26 to 24.96 μm, and from 0.04 to 8.64, respectively (Table 2). The variation of morphology of *D. giganteus* fibers was very significant. Wang et al. (2011) also observed the same results in *Fargesia yunnanensis*. Fiber length, tangential diameter, and W/Lu ratio plays an important role in evaluating the utilization value of bamboo fibers. Liese (1985) also considered that fiber length serves as an important criterion for pulping suitability. The mean fiber length of *D. giganteus* from the three sites was 2.34 mm, which was longer than that of *Bambusa pervariabilis* × *Dendrocalamopsis daii* (1.93 mm), *F. yunnanensis* (1.76 mm), *Guadua angustifolia* (1.60 mm), *P. edulis* (1.5 mm), *P. heteroclada* (1.58 mm), *Phyllostachys propinqua* (1.68 mm), *Pleioblastus maculata* (1.69 mm), *Qiongzhuea puberulla* (1.64 mm), and *Yushania uniramosa* (1.29 mm) but shorter than that of *Bambusa tulda* (3.00 mm) and similar to that of *B. sinospinosa* (2.37 mm), *B. blumeana* (2.27 mm), *B. vulgaris* (2.30 mm), *Dendrocalamus yunnannicus* (2.49 mm), *D. sinicus* (2.27 mm), *D. latiflorus* (2.37 mm), and *Gigantochloa scortechinii* (2.44 mm) (Liese 1995, Zhang 1995, Pu and Du 2003, Norul Hisham et al. 2006, Cao and Li 2010, Gou et al. 2010, Su et al. 2011, Wang et al. 2011). Therefore, *D. giganteus* is suitable for pulping and papermaking compared with the fiber lengths of other bamboo species. Besides, the L/T ratio for good pulp raw materials needs to reach above 100, and the larger, the better (Wang et al. 2008, Yang et al. 2008). The results shown in this study demonstrated that *D. gigantus*, with a mean value of 131.20, is suitable as a pulp raw material. Wang et al. (2008) had also measured the fiber morphology of the middle internode of the middle part of the 3-year-old culms of *D. giganteus* and considered it suitable as a pulp raw material.

Changes in fiber characteristics with age.—As shown in Table 3, fiber length differed slightly with age, and no specific trend was observed. It can also be noted that the tangential diameter increased slightly with age, while the L/T decreased accordingly. This agreed with the results of Gan and Ding (2006) that as soon as the height growth of culms is completed, the fibers will stop increasing their length and tangential diameter. Norul Hisham et al. (2006) also reported no significant difference for tangential diameter of fibers between different ages. Wang et al. (2011) reported that age does not have a significant influence on fiber length and tangential diameter and that fibers complete their length growth in 1 or 2 years. Therefore, the fiber of most bamboo species achieved its maximum length within 1 year after its culm achieved a maximum height.

Fiber wall thickness and W/Lu ratio increased gradually with age, and no specific trend was observed in lumen diameter (Table 3). Liese and Weiner (1996), as well as Murphy and Alvin (1997), reported a thicker fiber wall in older bamboos (3 to 12 yr). A similar trend was also reported by Gritsch et al. (2004) that the fiber cell wall thickness increased significantly from <6 months to 1 year old and from 1 to 3 years of age in *Dendrocalamus asper*. Fiber wall deposition can continue for 2 to 3 years, after the growth of fiber length and width have finished (Gan and Ding 2006, Wang et al. 2011). Fiber wall thickening is caused by the deposition of additional lamellae with age (Nordahlia et al. 2012). Wang et al. (2012) also reported that the 3-year-old culms of *F. yunnanensis* still have many thin-walled fibers that continue thickening in subsequent growing years.

Table 2.—Fiber basic index of all D. giganteus culm samples from all three sites.[a]

	Length, L (mm)	Tangential diameter, T (μm)	L/T	Wall thickness, W (μm)	Lumen diameter, Lu (μm)	W/Lu
Minimum	0.82	3.38	52.11	1.30	0.26	0.04
Maximum	6.42	31.46	680.33	22.88	24.96	8.64
Mean	2.34	19.05	131.20	5.68	7.69	1.48

[a] Number of measured fibers = 11,250.

Changes in fiber characteristics with height.—The fiber morphology was also significantly different with height (Table 3). Fiber length increased in descending order from middle to top to bottom for all age classes. The same trend was found in *F. yunnanensis* (Wang et al. 2011). Liese (1998) also considered that the mean fiber length of an internode is correlated with the internode length. This, however, was in contrast with *Dendrocalamus sinicus*, which had longer fibers at the bottom than at the middle and top sections (Pu and Du 2003). Abd Latif et al. (1990) also reported that there is no significant difference in fiber length along the culm height. The variability that exists along the culm of different bamboo species may be because of the different growth rates of the species (Abd Latif and Mohd Tamizi 1992).

As for the tangential diameters of fibers, no specific trend related to height was observed in *D. giganteus* between the three internodes. The fibers at the top, internode 17, had the thinnest walls but the largest lumina. This contributed to the smallest W/Lu ratio. Liese (1998) also reported that the fibers are generally thicker in the bottom section than in the top.

In relation to fiber length in internode 8, the results revealed that fiber length increased from section 1 (supranodal ridge) and achieved a maximum value at the middle of the internode (section 6) and then decreased toward section 10 (sheath scar) (Fig. 3). The same trend was found for tangential diameter but not in the case of lumen diameter. Lumen diameter fluctuated within the internode length, ranging from 4.62 to 9.94 µm. The shortest fibers were always located near the nodes, and the longest were found in the middle part of the internode. These findings are in agreement with those of Liese (1985, 1998).

Changes in fiber characteristics with site.—The average of fiber morphology of bamboo culms from the three different sites are shown in Table 4. Bamboo culms from Cangyuan County have a greater potential as raw materials for pulp and paper than those from Longchuan County and Simao County due to their longer fiber length and the lowest W/Lu ratio. Fiber characteristics varied significantly with site, which was in a good agreement with the studies on *B. chungii* (Yang et al. 2009). Abd Latif and Phang (2001) also reported that the mechanical properties of bamboo vary significantly with site. Therefore, the fiber properties in bamboo culms could be affected by external environmental conditions at different sites.

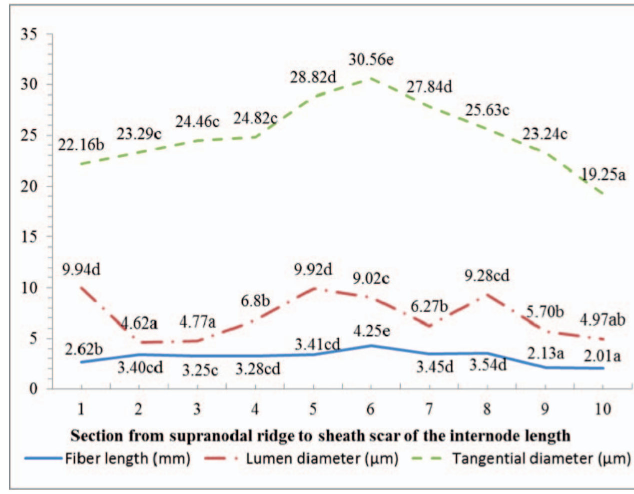

Figure 3.—The fiber characteristics of 10 sections from base (section 1) to top (section 10) in the middle internode of one 3-year-old culm from Longchuan County. Means followed by the same letters for comparison between different portions are not significantly different at 0.05 probability levels. (Color version is available online.)

Variation in chemical properties

Changes in chemical composition with age.—The chemical composition of *D. giganteus* varied with age (Table 5). The content of SiO_2 and ash increased from year 1 to year 2, but no significant difference was noted between ages 2 and 3. The SiO_2, alcohol-toluene extractive, holocellulose, and lignin contents increased slightly with age. These findings were not in agreement with those of Abd Latif et al. (1994), who found no clear trend between holocellulose content in 1- to 3-year-old *G. scortechinii*. However, Li et al. (2007), as well as Wang et al. (2011), considered that holocellulose content increases with age. The content of acid-insoluble lignin was shown to increase with age, while the acid-soluble lignin showed the opposite trend and decreased with age. Norul Hisham et al. (2006) also reported that lignin content increased dramatically with

Table 3.—Mean values of the fiber characteristics of D. giganteus *culms of all ages in Longchuan County.*[a]

Age (yr)	Height	Length, L (mm)	Tangential diameter, T (µm)	L/T	Wall thickness, W (µm)	Lumen diameter, Lu (µm)	W/Lu	*n*
1	Top	2.46 AB	15.81 A	155.60 BC	2.41 A	11.00 E	0.44 A	750
	Middle	2.76 BC	14.44 A	191.11 C	4.85 C	4.73 A	2.06 C	750
	Bottom	2.02 A	21.36 C	94.35 AB	7.46 E	6.44 B	2.32 D	750
	Mean	2.41 A	17.20 A	147.02 A	4.91 A	7.39 A	1.33 A	2,250
2	Top	2.08 A	17.89 B	116.27 AB	3.01 AB	11.88 F	0.51 A	750
	Middle	2.53 B	18.92 BC	174.19 C	6.34 D	6.24 B	2.03 C	750
	Bottom	1.91 A	19.66 BC	97.10 A	6.50 D	6.66 B	1.95 C	750
	Mean	2.17 A	18.82 AB	129.19 A	5.28 AB	8.26 B	1.28 A	2,250
3	Top	2.29 AB	16.12 AB	142.06 BC	3.65 B	8.89 D	0.82 B	750
	Middle	3.13 C	25.01 D	125.36 B	8.94 F	7.13 C	2.51 E	750
	Bottom	1.88 A	22.20 C	84.76 A	7.96 EF	6.27 B	2.54 E	750
	Mean	2.43 A	21.11 B	117.39 A	6.85 B	7.43 A	1.84 B	2,250

[a] Means followed by the same letters for comparison between different heights and ages are not significantly different at the 0.05 probability level. *n* = number of measured fibers.

Table 4.—Mean values of the fiber characteristics of 3-year-old culms between three sites in China.[a]

Site	Length, L (mm)	Tangential diameter, T (μm)	L/T	Wall thickness, W (μm)	Lumen diameter, Lu (μm)	W/Lu	*n*
Longchuan	2.43 A	21.11 B	117.39 B	6.85 B	7.43 B	1.84 A	2,250
Simao	2.59 AB	17.35 A	149.38 AB	6.60 B	4.16 A	3.22 B	2,250
Cangyuan	2.68 B	19.68 AB	136.01 A	5.96 A	7.76 B	1.54 A	2,250

[a] Means followed by the same letters for comparison between different sites are not significantly different at the 0.05 probability level. n = number of measured fibers.

age. A similar trend was also reported by Wang et al. (2011). The increasing content of lignin indicated the constant lignification in culms. In relation to the dynamic changes in chemical composition, Wang et al. (2011) considered that the increment of lignin content with age was mostly because of the increase in the number of cells with secondary thickening and lignification. Fiber wall thickening can continue constantly from year 1 to year 3 (Gritsch et al. 2004), so the lignin and holocellulose contents can increase gradually. Norul Hisham et al. (2006) observed no specific trend in the alcohol-toluene extractive, while both Li et al. (2007) and Wang et al. (2011) reported an increase of alcohol-toluene extractive content with age. Generally, the results suggest that the 3-year-old culms were suitable for utilization purposes, based on their low SiO_2 and ash contents but high holocellulose content.

Changes in chemical composition with height.—The chemical composition of *D. giganteus* was significantly different with height (Table 5). The silica oxide and ash contents were higher at the top and middle sections than at the bottom. The alcohol-toluene extractive also showed a similar trend, except in 2-year-old culms. Liese (1985) reported that the silica content varies on average from 0.5 to 4 percent, increasing from bottom to top. Li et al. (2007) also reported a similar trend for extractive and ash in *P. pubescens*. However, Wang et al. (2011) reported no specific trend with height in *F. yunnanensis*. This is probably species specific and suggests the need for further study.

In addition, the content of lignin and holocellulose were also higher in the top and middle sections than in the bottom for all age classes. A similar trend was also observed in *Bambusa wenchouensis*, *P. pubescens*, and *F. yunnanensis* (Su et al. 2005, Li et al. 2007, Wang et al. 2011). Cheng et al. (2015) also reported the similar trend in the Cangyuan provenance of *D. giganteus,* although they did not separately designate which internodes were the top, middle, and bottom. At the bottom of the culms, there is more parenchyma tissue than at the top, while the top had a relatively higher vascular bundle concentration. Therefore, the holocellulose content at the top was relatively higher (Wang et al. 2011).

Table 5.—Mean percent values of the major chemical constituents in D. giganteus culms from Longchuan.[a]

Age (yr)	Position	SiO_2	Ash	Alcohol-toluene extractive	Lignin	Holocellulose
1	Top	2.32 F	3.08 E	2.59 C	22.62 B	64.93 A
	Middle	0.85 E	2.41 D	1.45 B	22.53 B	71.91 B
	Bottom	0.20 A	2.26 C	0.71 A	19.79 A	63.07 A
	Mean	1.12 A	2.58 A	1.58 A	21.65 A	66.64 A
2	Top	2.34 F	3.43 F	1.63 B	26.43 CD	71.00 B
	Middle	0.44 B	1.63 B	2.33 C	25.38 C	73.70 C
	Bottom	0.39 B	3.16 E	0.92 A	19.83 A	66.93 A
	Mean	1.24 B	2.74 A	1.63 A	23.88 AB	70.54 AB
3	Top	3.14 G	4.45 G	3.06 D	27.35 D	70.94 B
	Middle	0.46 B	1.20 A	0.72 A	27.81 D	71.35 B
	Bottom	0.71 D	1.19 A	1.40 B	25.86 C	70.10 B
	Mean	1.23 B	2.28 A	1.73 A	27.01 B	71.13 B

[a] Means followed by the same letters for comparison between different portions and ages are not significantly different at the 0.05 probability level.

Changes in chemical composition with site.—All the chemical constituents of 3-year-old bamboo culms were significantly different with site, as shown in Table 6. Bamboo culms grown in Longchuan County had the highest silica oxide and lignin contents but the lowest alcohol-toluene extractive and holocellulose contents, which were 1.23, 27.01, 1.73, and 71.13 percent, respectively. Bamboo culms grown in Cangyuan County had the lowest silica oxide and lignin contents but the highest holocellulose content compared with other sites. Therefore, bamboo culms from Cangyuan County were the most suitable to use as raw materials for pulp and paper than those from other sites.

In relation to the variation of chemical compositions in bamboo culms from different sites, Yang et al. (2009) reported a similar trend for *B. chungii*. In contrast, Wang et al. (2011) reported that the chemical compositions of bamboo culms were not significantly different with geographical site, except for holocellulose. Therefore, the bamboo properties were not only influenced by age and geographic conditions but also by the species itself, which needs to be considered for further processing into any products. In addition, Wang et al. (2009) considered that it is important to select the most suitable provenance for popularization as timber-purpose bamboo. The *D. giganteus* bamboos from Cangyuan County were the best provenance for popularization and for pulping and processing owing to having the longest fibers, the lowest W/Lu ratio, the lowest

Table 6.—Mean percent values of the major chemical constituents in 3-year-old culms from three sites.[a]

Site	SiO_2	Ash	Toluene-alcohol extractive	Lignin	Holocellulose
Longchuan	1.23 C	2.28 B	1.73 A	27.01 C	71.13 A
Simao	0.44 A	1.67 A	4.52 C	24.65 B	73.57 B
Cangyuan	0.76 B	2.74 C	2.80 B	22.97 A	76.88 C

[a] Means followed by the same letters for comparison between different sites are not significantly different at the 0.05 probability level.

SiO_2 and lignin contents, and the highest holocellulose content.

Conclusions

1. Bamboo properties differed with age, height, and geographical site. The fiber was longest at the middle internode of the culm height and at the middle section of the internode length. Fiber length, tangential diameter, and L/T were not significantly different with age. Fiber wall thickness and W/Lu ratio increased with increasing age and were highest in 3-year-old culms.
2. The top internode had higher SiO_2 and ash contents but lower alcohol-toluene extractives, lignin, and holocellulose contents than those from other internodes for all age classes. SiO_2, holocellulose, and lignin contents slightly increased with age. Three-year-old *D. giganteus* contained the highest amount of holocellulose but the lowest SiO_2 content and was found to be more suitable for any utilization purpose.
3. Bamboo culms from Cangyuan County had the most potential to be used as raw materials for pulp and paper than those from the other geographical sites, and therefore the Cangyuan provenance was also more suitable for popularization.

Acknowledgments

The project was fully funded by the national ''Twelfth Five-Year'' scientific and technological support plan subject (2012BAD23B05) and the National Natural Science Fund of China (31560196). We are grateful to Dr. Todd F. Shupe, Louisiana State University Agricultural Center, for his kind help.

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