Variability of Anatomical and Chemical Properties with Age and Height in *Dendrocalamus brandisii*

Yujun Wang,[a] Hui Zhan,[a] Yulong Ding,[b] Shuguang Wang,[a,]* and Shuyan Lin [b]

Dendrocalamus brandisii is an edible bamboo species found in Southwest China and South Asia. However, there is limited information about the anatomical and chemical information of its culms for its utilization and processing. In this paper, the anatomical and chemical properties of different age culms were determined. There are three vascular bundle types found in its culms. The radial length-to-tangential diameter ratio of vascular bundles varied with culm zone but did not vary with age. The outer diameter of metaxylem vessels showed a similar trend. The fiber length (L), wall thickness (W), and Runkel ratio increased with age, while the fiber length-to-outer diameter ratio (L/D) and lumen diameter (Ld) decreased with age. The chemical properties of *D. brandisii* also differed with age class and height. The holocellulose and ash content decreased from age 1 to 2 years and then increased at year 3. The acid-insoluble lignin, alcohol-toluene extractives, and silica contents increased with age class, whereas the acid-soluble lignin exhibited the opposite trend. The fiber length and L/D values of *D. brandisii* suggest it would be suitable material for pulp fibers, but its lignin content was relatively high compared with other bamboo species.

Keywords: Dendrocalamus brandisii; Vascular bundle type; Fiber morphology; Chemical properties

Contact information: a: Faculty of Life Science, Southwest Forestry University, Kunming 650224, China; b: Bamboo Research Institute, Nanjing Forestry University, Nanjing 210037, China;
** Corresponding author: stevenwang1979@126.com*
Yujun Wang, Hui Zhan, Yulong Ding, Shuguang Wang, and Shuyan Lin contributed equally to this work.

INTRODUCTION

Chemical and anatomical properties are important factors that influence the mechanical strength of bamboo culm (Liese 1985). Bamboo is an attractive alternative to timber because of its short crop rotation and favorable mechanical properties for utilization as medium density fiberboard as well as pulp and paper products (Janssen 1995; Ahmad 2000; Hammett *et al*. 2001; Wang *et al*. 2011). Generally, bamboo culms reach maturity between 3 and 4 years after cultivating and then their nutrition contributions for bamboo clump begin to decrease (Banik and Islam 2005). Hence, mature culms should be harvested at the proper time to keep bamboo stands healthy and to promote the growth of new shoots. The properties and uses of bamboos are influenced by structural changes related to aging, and the maturing time limits the commercial harvest age (Liese and Weiner 1996; Li *et al.* 2007). The physical and mechanical properties were correlated to the anatomical characteristics (Abd. Latif *et al*. 1993). Information on anatomical and chemical properties of bamboo is necessary for assessing its suitability for various end products. The appropriate use of any material depends on its properties to a large extent (Kamruzzaman *et al.* 2008). For example, Norul Hisham *et al.* (2006) reported that the bamboo culms with high content of inorganic nutrients showed the potential as the chewing sticks and the bamboo culms from 3.5 years of age was suitable for any utilization purpose. Significant correlation was also found between the vascular bundle density and the mechanical properties of bamboo plywood (Qi *et al.* 2014). Therefore, studies on the relationships between culm age and anatomical and chemical properties will aid in the processing and utilization of bamboo (Wang *et al*. 2011).

Dendrocalamus brandisii is a sympodial bamboo species, primarily found in the Yunnan province of China and sporadically found in Burma, Laos, Vietnam, and Thailand (Li *et al*. 2006; Viswanath *et al*. 2013). In the local regions of Southwest China, people eat the new shoots, which are sweet and have nutritional value. However, in bamboo forestry operations, the mature culms are often cut and discarded or used in households as fuel. Its potential for large-scale industrial utilization has yet to be explored in detail. Accordingly, the goal of this study was to explore the chemical and anatomical properties of *D. brandisii*, which will assist in the utilization and processing of this raw material by the forest products industry.

EXPERIMENTAL

Materials

Bamboo culms of three age classes (1, 2, and 3 years old) were collected from Daxintian village (101°05′ E, 22°42′ N), which is located in Puer city of Yunnan province, China. The culm age was determined by monitoring the growth of new shoots.

Five culms of each age class with similar diameters were selected and harvested. Each culm was divided into three portions, as delineated by various internodes: the second internode for the bottom portion, the twelfth internode for the middle, and the twenty-fourth internode for the top. Five samples from each portion were cut into small pieces and fixed in an aqueous FAA solution (45% ethanol, 0.25% acetic acid, and 1.85% formaldehyde) for microscopy. All samples were transported to the laboratory and stored at room temperature until further processing.

Methods

Determination of anatomical properties

After fixation in FAA solution, the samples were preserved in a mixture of 50% ethanol, 10% glycerin, and 40% water (Lybeer *et al*. 2006). Transverse sections of the culms were cut to 15 to 20 μm in thickness using a sliding microtome (Leica SM2010 R, Germany). Sections were stained with 1% Safranin O (Sigma S-2255) in 50% ethanol, rinsed with distilled water, counter-stained in 1% aqueous Alcian Blue (Fluka 05500), and dehydrated in a graded series of ethanol. All sections were permanently mounted in Canada balsam, so as to be observed repeatedly and stored forever (Wang *et al*. 2011). A total of 100 vascular bundles were measured for radial length/tangential diameter ratio (Fig. 1 C) and outer diameter of the metaxylem vessel. All sections were observed with a video camera linked to a converted microscope (Nikon E400, Japan) and a Lenovo computer.

Samples for fiber measurements were macerated in Jeffrey's solution containing 10% aqueous nitric acid and 10% aqueous chromic acid (Jeffrey 1917) and heated at 60 °C for 72 to 96 h. A total of 150 fibers from each sample were measured to determine length, outer diameter, wall thickness, lumen diameter, and Runkel ratio (2×wall thickness/lumen diameter) (Saikia *et al.* 1997; Norul Hisham *et al*. 2006).

Determination of chemical properties

Samples of each age class were cut into small strips containing the outer and inner culm skin, oven dried at 60 °C for 24 h, and ground in a Wiley mill. The ground material was placed in a shaker, and the particles that passed through a no. 40 mesh sieve but were retained on a no. 60 mesh were used for subsequent chemical analysis. The amounts of alcohol-toluene extractives, holocellulose, lignin, silica, and ash were determined using the standard methods of the Chinese National Standard for Testing and Materials (GB/T 7978-1987, GB/T 10741-1989, GB/T 2677.3-1993, GB/T 2677.8-1994, GB/T 2677.10-1996, and GB/T 10337-2008).

Statistical analyses were carried out using SPSS 13.0 (SPSS, Inc., Chicago, IL). The least significant difference method (LSD) was employed to analyze the difference from the mean values derived from the experiments.

RESULTS AND DISCUSSION

Vascular Bundle Properties

The anatomical properties of the culms affect the physical and mechanical properties of the bamboo wood, which also affect the preservation and final utilization of this wood (Wang *et al*. 2011). Three vascular bundle types from the outer to the inner zone in *D. brandisii* culms were observed—the semi-undifferentiated type, the broken-waist type, and the double broken-waist type (Fig 1. A, B, and C, respectively)—in accordance with the classifications denoted by Wen and Chou (1984). The double broken-waist type consists of three parts: the central vascular strand with small sclerenchyma sheaths and two isolated fiber bundles located at the phloem and the protoxylem side. The broken-waist type consists of two parts: the central vascular strand and an isolated fiber bundle located at the protoxylem side (Liese 1998). The semi-undifferentiated type consists of just one central vascular strand, and their metaxylem and protoxylem fiber bundles are often fused together.

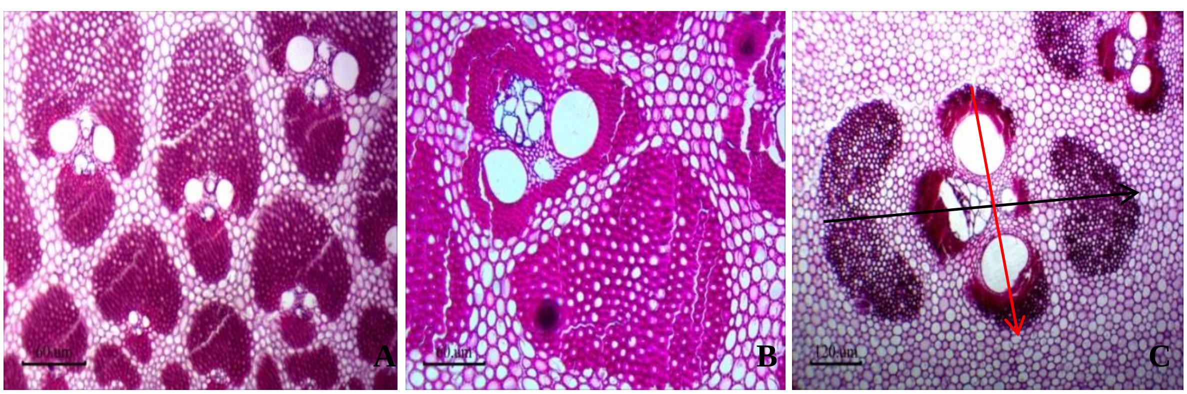

Fig. 1. The vascular bundle types of *D. brandisii* in transverse section: A, semi-undifferentiated type in outer zone; B, broken-waist type in middle zone; and C, double broken-waist type in inner zone. The black and red arrows represent the radial length and tangential diameter of vascular bundles, respectively.

Radial Length/Tangential diameter Ratio of Vascular Bundles

This ratio decreased significantly both from the outer zone to the inner zone and from the top to the bottom for all age classes. Notably, the ratio was close to 1 for the inner zone and the bottom of the culms, but it was close to 2 for the outer zone and the top. These observations implied that there were much higher vascular bundle concentrations at the outer zone and at the top of the culms (Table 1 and Fig. 1), which is in agreement with previous reports (Grosser and Liese 1971; Wang *et al*. 2011; Huang *et al*. 2015). Similar trends were also reported for the bamboo species *Guadua anguistifolia* (Londoño *et al*. 2002) and *Gigantochloa scortechinii* (Norul Hisham *et al.* 2006). Vascular bundles were longer and smaller at the outer zone but shorter and larger towards the inner zone (Wang *et al.* 2011). Thus, smaller vascular bundles tended to be denser in distribution than the larger ones, and the outer zones had higher density and mechanical strength than the inner zones (Zhou 1981; Liese 1985). Primary tissue and parenchyma cells increased gradually from the outer towards the inner zones (Liese 1985; Anonymous 2001). The top portions of the culms had a smaller ratio than the bottom, which could be due to the tapering structure of the culms (Abd. Latif and Mohd. Tamizi 1992). Similarly, within the culm wall, the total number of vascular bundles decreased from the bottom towards the top, while their density increased (Liese 1985).

No significant differences were observed for the ratio for the various age classes, which implied that the morphological structure of the vascular bundles stabilized once the culms ceased growing in height. Norul Hisham *et al*. (2006), as well as Wang *et al*. (2011), reported that the age of the culms affected the ratio to a certain extent. However, Grosser and Liese (1971), as well as Abd. Latif and Mohd. Tamizi (1992), reported that culm age did not significantly affect the radial length/tangential diameter ratio. Generally, numerous factors can affect this ratio, such as individual bamboo species, culm diameter, culm walls thickness, and culm height.

Table 1. Radial Length/Tangential Diameter Ratio of Vascular Bundles

Age (Years)	Position	Fiber Length/Outer Diameter (μm/μm)			Means
		Outer	Middle	Inner	
1	Top	1.51±0.03Ac	1.25±0.06Ab	0.88±0.01Aa	1.21±0.08A
	Middle	1.63±0.03Ab	1.51±0.06Aab	0.92±0.03Aa	1.35±0.09AB
	Bottom	2.60±0.09Bc	2.10±0.07Bb	1.50±0.04Ba	2.07±0.14B
	Means	1.91±0.15b	1.62±0.11b	1.10±0.09a	1.54±0.18A
2	Top	1.76±0.06Ab	1.58±0.05Ab	0.80±0.07Aa	1.38±0.13A
	Middle	1.83±0.04Ab	1.62±0.11Ab	1.15±0.06Ba	1.53±0.09A
	Bottom	2.25±0.07Bb	2.00±0.14Bb	1.21±0.09Ba	1.82±0.14A
	Means	1.95±0.07b	1.73±0.08b	1.05±0.07a	1.58±0.15A
3	Top	1.85±0.02Ac	1.18±0.04Ab	0.87±0.05Aa	1.30±0.12A
	Middle	1.88±0.11Ac	1.62±0.02Bb	1.18±0.02Ba	1.56±0.09A
	Bottom	2.53±0.11Bb	2.40±0.03Cb	1.33±0.09Ba	2.09±0.17B
	Means	2.09±0.11b	1.73±0.15b	1.13±0.06a	1.65±0.19A

Means with the same uppercase letter in each column and means with the same lowercase letter in each line are not significantly different at 0.05 probabilities.

Outer Diameter of Metaxylem Vessel

The outer diameter of the metaxylem vessel in *D. brandisii* increased slightly with age from 139.42 to 162.04 μm (Table 2). While a similar trend is observed for *Bambusa rigida*, there is a significantly increasing trend with age for *G. scortechinii* (Norul Hisham *et al*. 2006; Huang *et al*. 2015). This dissimilarity might be caused by individual differences between bamboo species. In addition, the diameter of the metaxylem vessel increased from the outer zone toward the inner zone at all age classes, which was consistent with the fiber length/outer diameter ratio of vascular bundles observed in this study and previous reports (Liese 1985; Norul Hisham *et al*. 2006; Wang *et al*. 2011). Vessels at the outer perimeter of the culm are smaller than those in the middle and inner perimeters (Liese 1998). Bamboo supporting tissues were mainly distributed at the outer zone, where the fiber bundles developed very well, but the vessels developed incompletely. The mean diameter of the metaxylem vessel decreased slightly with culm height for all age classes. Similarly, Huang *et al*. (2015) reported a slight decreasing trend from bottom to top, which could be due to the variation in culm wall thickness versus culm height.

Table 2. Outer Diameter of Metaxylem Vessels

Age (Years)	Position	Outer Diameter of Metaxylem Vessel (μm)			Means
		Outer	Middle	Inner	
1	Top	40.17±2.66Aa	124.97±5.66Ab	187.53±7.97Ac	117.55±18.46A
	Middle	63.43±0.43Ba	130.59±4.54Ab	225.94±4.02Bc	139.99±20.19A
	Bottom	75.19±1.99Ca	170.05±6.39Bb	236.94±2.17Bc	160.73±20.12A
	Means	59.60±4.50a	141.87±6.71b	216.80±6.96c	139.42±23.65A
2	Top	42.02±4.54Aa	104.77±2.27Ab	207.30±9.25Ac	118.03±20.79A
	Middle	49.58±2.63Aa	146.02±3.01Bb	254.85±2.77Bc	150.15±25.32A
	Bottom	66.74±3.57Ba	192.49±8.45Cb	259.91±8.70Bc	173.05±24.43A
	Means	52.78±3.66a	143.15±37.03b	240.69±8.15c	147.07±28.58A
3	Top	60.64±4.37Aa	141.31±4.73Ab	189.90±6.20Ac	130.62±16.30A
	Middle	71.14±1.61Ba	152.69±4.70Ab	242.30±4.50Bc	194.58±21.17A
	Bottom	75.06±3.16Ba	196.54±6.75Bb	249.84±5.22Bc	155.78±22.22A
	Means	68.95±2.50a	163.51±7.73b	227.35±8.51c	162.04±24.17A

Means with the same uppercase letter in each column and means with the same lowercase letter in each line are not significantly different at 0.05 probabilities.

Fiber Properties

Changes in fiber dimension

Table 3 shows the fiber length (*L*), outer diameter (*D*), length/outer diameter (*L*/*D*), wall thickness (*W*), lumen diameter (*Ld*), and Runkel ratio for *D. brandisii*. The fiber length of *D. brandisii* ranged from 0.82 to 6.41 mm with a mean of 2.52 mm, which indicated that these fibers were long (Yang *et al*. 2008; Wang *et al*. 2008). The outer diameter of the fibers ranged from 3.38 to 31.46 μm with mean of 17.63 μm. The mean value of Runkel ratio was 3.98. Fiber length, outer diameter, and Runkel ratio values influence the utilization value of bamboo. Fiber length is an important criterion for bamboo pulping (Liese *et al*. 1985). The mean fiber length of several commercial bamboo species have been measured, including *Bambusa tulda* (3 mm), *B. vulgaris* (2.3 mm), *Dendrocalamus giganteus* (3.2 mm), *Guadua angustifolia* (1.6 mm), *Phyllostachys edulis* (1.5 mm), and *Fargesia yunnanensis* (1.76 mm) (Li *et al.* 2006; Wang *et al*. 2011). The fiber length of *D. brandisii* is comparable to other bamboo species and is thus suitable for pulping and papermaking. The *L*/*D* ratio of pulp fibers for papermaking should be above 100 μm/μm, and a larger ratio is better (Wang *et al.* 2008; Yang *et al*. 2008). The mean value for *D. brandisii* was 154.63 μm/μm, which may be suitable for papermaking.

Table 3. Basic Fiber Index of *Dendrocalamus brandisii*

	Length, *L* (mm)	Outer Diameter, *D* (μm)	*L*/*D* (μm/μm)	Wall Thickness, *W* (μm)	Lumen Diameter, *Ld* (μm)	Runkel ratio (μm/μm)
Maximum	6.41	31.46	680.10	12.09	24.96	59.00
Minimum	0.82	3.38	52.09	0.26	0.26	0.15
Mean	2.52±0.11	17.63±0.90	154.63±8.56	5.89±0.49	6.05±0.53	3.98±0.56

Note: The data were the average of the characteristic index of all measured fibers.

Changes in fiber morphology with age

Fiber length and *L*/*D* decreased slightly with age, with the highest mean value observed for the 1-year-old culms (Table 4). Similarly, there was no significant difference in outer diameter between the different age culms, and the highest mean value was observed for the 2-year-old culms. Thus, the fiber length and outer diameter of *D. brandisii* did not change after the first year of growth. This result agreed with a previous report that as soon as the culms reach their maximum height, the length and outer diameter of the fibers do not increase further (Gan and Ding 2006). Norul Hisham *et al*. (2006) also reported no significant differences for the outer diameter of fibers between different age classes. Culm age has a significant influence on fiber length and outer diameter, and fibers complete their width growth in one or two years (Wang *et al.* 2011).

The wall thickness was higher in the top and middle segments of 2- and 3-year-old culms, while the fiber lumen diameter was lower in the top, suggesting that the deposition secondary fiber walls was higher in the top than in the middle and bottom culm portions. The Runkel ratio slightly increased with regard to culm height, with the highest mean value found at the top. Fiber wall thickness also increases with culm age and culm height for *Bambusa vulgaris* and *Gigantochloa levis* (Abd. Latif and Mohd. Tamizi 1992; Nordahlia *et al.* 2012).

Chemical Properties

Changes in chemical composition with age

Chemical composition of the culms is an important factor that influences the utilization of bamboo wood. As shown in Table 5, the holocellulose content decreased considerably from age class 1 to 2 years but then increased slightly at year 3. The highest holocellulose content was found in 1-year-old culms, which is mainly due to their lower lignification. However, there is no observable trend in the holocellulose content *versus* age for 1- to 3-year-old *G. scortechinii* (Abd. Latif *et al.* 1994). Li *et al.* (2007) and Wang *et al.* (2011) indicated that holocellulose content increases with culm age. In this study, the acid-insoluble lignin content increased with age, while the acid-soluble lignin showed the opposite trend. Lignin content dramatically increased from 0.5 to 1.5 years but gradually increased thereafter, as observed previously (Norul Hisham *et al.* 2006; Wang *et al.* 2011). The fiber wall thickening rate was constant from year one to year three, as lignin and holocellulose contents have been shown to increase gradually (Gritsch *et al.* 2004). Moreover, the alcohol-toluene extractives showed an increasing trend with age, with the highest average at 2.06% for a culm age of 3 years. This result differed from a previous report showing no specific trend for alcohol-toluene extractives (Norul Hisham *et al.* 2006). However, Li *et al.* (2007) and Wang *et al.* (2011) both reported an increase of alcohol-toluene extractives with culm age.

Table 4. Age- and Height-Based Variations in *Dendrocalamus brandisii* Fibers

Age Class	Position	Length *L* (mm)	Outer Diameter, *D* (μm)	*L*/*D* (μm/μm)	Wall Thickness, *W* (μm)	Lumen Diameter, *Ld* (μm)	Runkel ratio (μm/μm)
1	Top	1.99±0.11a	12.44±0.41b	159.97±10.60a	3.65±0.11a	5.13±0.49a	1.42±0.18b
	Middle	2.90±0.08b	18.67±0.76c	155.33±6.53a	4.67±0.24b	9.33±0.82c	1.00±0.20a
	Bottom	3.17±0.19b	14.86±0.59a	213.32±13.05b	3.72±0.17a	7.43±0.64b	1.00±0.25a
	Mean	2.69±0.09a	15.32±0.40a	176.21±6.37a	4.01±0.11a	7.30±0.40a	1.10±0.12a
2	Top	2.14±0.08a	16.89±0.75a	126.70±13.36ab	6.80±0.29b	3.30±0.34a	4.12±1.17b
	Middle	2.69±0.10b	23.46±0.64b	114.66±5.25a	8.35±0.31c	6.76±0.54b	2.47±0.39a
	Bottom	2.69±0.13b	17.63±0.71a	152.58±7.75b	4.73±0.33a	8.17±0.88b	1.16±0.48a
	Mean	2.51±0.07a	19.33±0.47a	131.31±5.57a	6.63±0.21b	6.08±0.40a	2.58±0.48ab
3	Top	2.11±0.08a	18.82±0.97b	112.11±5.14a	7.34±0.38b	4.14±0.35a	3.55±0.69a
	Middle	2.68±0.07b	20.52±0.67b	130.60±8.20b	7.49±0.33b	5.54±0.76a	2.70±1.23a
	Bottom	2.30±0.11a	15.35±0.58a	149.84±5.61b	5.34±0.22a	4.67±0.50a	2.29±1.21a
	Mean	2.37±0.05a	18.23±0.47a	130.85±3.85a	6.72±0.20b	4.79±0.33a	2.85±0.62b
Mean	Top	2.08±0.05a	16.05±0.48a	132.93±6.09a	5.93±0.21a	4.19±0.24a	3.03±0.50a
	Middle	2.76±0.05b	20.88±0.43a	133.53±4.17a	6.84±0.21a	7.21±0.43a	2.05±0.45a
	Bottom	2.72±0.09b	15.95±0.37a	171.91±5.96a	4.60±0.15a	6.76±0.42a	1.42±0.45a

Means with the same letter in the same column are not significantly different at 0.05 probabilities.

Silica is primarily located in the culm epidermis; it serves as a barrier to insects. High ash content, however, can adversely affect the machinery used to process bamboo and the chemical recovery of alkaline pulping liquors (Wang *et al.* 2011). The ash content of the culms decreased from 1- to 2-year-old samples but then increased in 3-year-old samples. The silica content increased with increasing culm age, with the highest average of 1.65% occurring in the 3-year-old culms. A similar trend was also reported for *G. scortechinii* (Norul Hisham *et al*. 2006) and for *F. yunnanensis*. However, Li *et al.* (2007) reported the highest silica content in 1-year-old culms. The high ash content of 1-year-old culms might be primarily caused by their higher moisture and lower dry matter contents, since all means were calculated based on dry weights.

Table 5. Chemical Composition of *Dendrocalamus brandisii* (%)

Age (years)	Position	Holocellulose	Acid-Insoluble Lignin	Acid-Soluble Lignin	Alcohol-Toluene Extractive	Ash	Silica
1	Top	73.12±0.42a	20.40±0.96a	3.66±0.07a	0.47±0.10a	3.70±0.30c	0.75±0.19b
	Middle	75.27±0.66b	21.28±1.70a	3.38±0.20a	1.29±0.15b	3.02±0.35b	0.28±0.06a
	Bottom	74.15±0.24ab	25.45±1.18b	3.25±0.08a	1.32±0.23b	2.24±0.24a	0.50±0.06ab
	Mean	74.18±0.39b	22.38±1.02a	3.43±0.09b	1.03±0.16a	2.99±0.26b	0.51±0.08a
2	Top	69.52±0.50a	29.23±1.56a	3.33±0.08a	2.37±0.56b	2.00±0.29a	1.11±0.41a
	Middle	71.43±0.25ab	29.28±0.98a	3.43±0.12a	2.09±0.39ab	1.92±0.18a	0.44±0.07a
	Bottom	73.12±0.98b	30.26±0.62a	3.15±0.16a	0.75±0.12a	2.32±0.44a	0.46±0.08a
	Mean	71.36±0.61a	29.59±0.58b	3.30±0.07ab	1.74±0.32b	2.08±0.17a	0.67±0.16a
3	Top	71.49±0.51a	32.07±0.38b	2.95±0.02a	2.23±0.16ab	4.03±0.77b	3.29±0.80b
	Middle	73.33±0.58a	27.64±0.59a	2.85±0.04a	2.35±0.23b	2.14±0.26a	1.18±0.17b
	Bottom	72.74±0.83a	26.44±1.02a	3.04±0.10a	1.60±0.13a	2.16±0.18a	0.48±0.08a
	Mean	72.52±0.42a	28.72±0.93b	2.95±0.04a	2.06±0.15b	2.78±0.39ab	1.65±0.48b
Mean	Top	71.38±0.57a	27.23±1.84a	3.31±0.11a	1.69±0.35a	3.24±0.40b	1.71±0.48b
	Middle	73.34±0.61b	26.07±1.37a	3.22±0.12a	1.91±0.21a	2.36±0.22a	0.63±0.15a
	Bottom	73.33±0.43b	27.38±0.88a	3.14±0.07a	1.22±0.15a	2.24±0.16a	0.48±0.04a
	Mean	72.69±0.35	26.90±0.79	3.23±0.06	1.61±0.15	2.61±0.18	0.94±0.19

Means with the same letter in the same column are not significantly different at 0.05 probabilities.

The mean values of the main chemical constituents in 3-year-old culms were 2.06 ± 0.15% for alcohol-toluene extractives, 72.52 ± 0.42% for holocellulose, 28.72 ± 0.93% for acid-insoluble lignin, 2.95 ± 0.04% for acid-soluble lignin, 2.78 ± 0.39% for ash, and 1.65 ± 0.48% for silica (Table 1). The holocellulose content of *D. brandisii* was higher than in other bamboo species, such as *Bambusa wenchouensis* (41.04%), *Phyllostachys pubescens* (71.70%), *Dendrocalamus latiflorus* (41.04%), and *F. yunnanensis* (57.59 to 74.30%) (Su *et al*. 2005; Li *et al*. 2007; Yang *et al.* 2007; Wang *et al*. 2011). Additionally, the acid-insoluble lignin content of *D. brandisii* was higher than that of *B. wenchouensis* (22.64%), *G. scortechinii* (27.80%), *P. pubescens* (22.77%), *D. latiflorus* (22.76%), and *F.*

yunnanensis (23.39-27.71%). High-yield pulp used to make newsprint contains most of the lignin originally present in the wood (Azooz and Ahmad 2016). Therefore, *D. brandisii* may be suitable for making newsprint-type papers. Lignin derivatives also contributed to the denser foams in crude bio-polyols (Xie *et al.* 2013).

Changes in chemical composition with height

The holocellulose content was higher in the middle portion than in the bottom or top portion of the culms at all age classes (Table 5). The acid-insoluble lignin content was higher in the bottom portion than in the middle and top portions, with significant differences in the 1-year culms but slight differences in the 2-year culms; it decreased with height in the 3-year-old culms. The highest value for the acid-soluble lignin was found in the top portion of the 1-year-old culms, the middle portion of the 2-year-old culms, and the bottom portion of the 3-year-old culms; however, the difference between the portions was insignificant at all age classes. The highest holocellulose content in the middle portions at all age classes could be related to the differences in vascular bundle concentration, number of parenchyma cells, and lignin content. The top portions had higher vascular bundle and lignin concentrations. Wang *et al*. (2011) indicated that there are relatively more parenchyma tissues in the bottom compared with the top and middle portions, while the top has higher vascular bundle concentrations. The top portion also has higher lignin content than the other culm portions. Thus, this high lignin content reduced the percentage of holocellulose in the top portions.

No specific trend in ash content was observed for the different portions at all age classes; however, the silica content was higher in the top portions than in the middle and bottom portions for all age classes (Table 4), as previously observed for silica in *P. pubescens* (Li *et al*. 2007). Wang *et al*. (2011) also observed that both ash and silica content decreased with culm length, with the highest values found in the top portion.

CONCLUSIONS

1. There are three types of vascular bundles in *D. brandisii* culms: *i.e*., undifferentiated, broken-waist, and double broken-waist.
2. The fiber length/outer diameter ratio of vascular bundles decreased from the outer zone to the inner zone and from the top to the bottom portions of the culms; however, no significant differences were observed between the ratios in different age classes. The outer diameter of the metaxylem vessels showed a similar trend.
3. The fiber wall thickness and *W*/*Ld* ratio increased with age class, while the fiber length, *L*/*D* ratio, and lumen diameter decreased with age class. In addition, the mean fiber length, outer diameter, wall thickness, and lumen diameter were higher in the middle portion of the culms than in other portions.
4. The chemical properties of *D. brandisii* culms differed with age class and height. The holocellulose and ash content decreased from age 1 to 2 years and then increased at age 3 years. The acid-insoluble lignin, alcohol-toluene extractives, and silica content increased with age class, while the acid-soluble lignin decreased with age class. The lignin content in mature culms was high compared with other bamboo species.

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