Chemical Properties and Fiber Morphology of *Fargesia fungosa* at Different Culm Ages and Heights

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The chemical properties and fiber morphology of *Fargesia fungosa* at different culm ages and height portions were investigated. The variations in moisture, ash, SiO_2, and toluene–alcohol extractive contents with culm ages were greater than they were with heights. The holocellulose varied neither significantly with age nor with height. The fiber length, width, length-to-width ratio, and wall thickness of *F. fungosa* increased with culm ages. Meanwhile, the middle portions of culms at all age classes had the highest values of fiber length and width. The lumen diameter decreased, whereas the wall-lumen ratio increased, with increasing bamboo ages and heights. The 3-year-old culms of *F. fungosa* are suitable for pulp and papermaking based on their fine chemical properties and fiber morphology.

Keywords: Fargesia fungosa; Chemical properties; Fiber morphology; Culm

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INTRODUCTION

Bamboo is considered to be one of the non-wood forest resources with the greatest potential as an alternative to wood resources due to its easy propagation, fast growth, and high yield. It provides an important raw material for the pulp and paper industry, especially in Southeast Asia (Hammett *et al*. 2001). Bamboo properties differ with species, age, location, and external factors (Grosser and Liese 1971; Janssen 1991; Abd Latif 1993). Abd Latif and Phang (2001) reported that the mechanical properties of bamboo in tropical countries, such as Malaysia, vary significantly with locations.

The chemical properties and fiber morphology in relation to culm ages and height positions is fundamental in the processing and utilization of bamboo timber. However, there are only a few bamboo species for which such aspects have been reported (Norul Hisham *et al.* 2006; Li *et al.* 2007; Correal *et al*. 2010; Nordahlia *et al*. 2011; Wang *et al*. 2011; Nordahlia *et al*. 2012). In *Phyllostachys pubescens*, Li *et al.* (2007) considered that holocellulose varied significantly with age and height, while Klason lignin did not vary significantly with height but did with age. Nordahlia *et al*. (2012) also reported that all the properties of *Gigantochloa levis* were not affected by age except for fiber wall thickness, which was thicker in 4-year-old bamboo culms. However, Wang *et al.* (2011) considered that fiber and chemical properties varied significantly with age and height portions. Properties and utilization of bamboos were reported to be influenced by structural changes brought about by aging (Liese 1997). The relation between bamboo aging and maturation was reviewed by Liese and Weiner (1996). Hence, understanding the relationship between culm ages and heights with anatomical and chemical properties is important in the processing and utilization of bamboo.

Bamboo is a promising natural resource with broad utilization advantages in Yunnan as well as elsewhere in China. Yunnan hosts about 200 bamboo species from 28 genera, which is over 50% of China's total, and the natural bamboo forest accounts for about 90% of the total bamboo forest (Wang *et al*. 2008). In recent years, bamboo plantation is expanding rapidly as an alternative to depleting timber resources. Distributed mainly in Southwest China, especially in Yunnan Province, *Fargesia fungosa* is the most abundant resource that is locally available for supplying construction wood, edible bamboo shoots, and highly elastic bamboo strips for weaving household and farm tools in the region. However, due to a lack of knowledge about the chemical properties and fiber morphology of *F. fungosa*, its potential for large-scale industrial utilization, *e.g.*, as raw pulp material, has yet to be further explored. Accordingly, this study endeavors to determine the effects of age and height on the chemical properties and fiber morphology of *F. fungosa* bamboo culms.

EXPERIMENTAL

Materials

Three bamboo culms of *F. fungosa* with diameters from 6.7 to 9.8 cm in each of the three age groups (1, 2, and ≥ 3 years old) were cut at about 20 cm above ground level. Three samples from each age group were used for replication. All bamboo samples were obtained from the Bamboo Garden of Southwest Forestry University, Kunming in China. The culm age was estimated based on visual inspection of culm color, extent of culm sheath decay, and surface lichen growth. For *F. fungosa*, the basal sections of 1-year-old culms are enclosed by culm sheaths and the culm skin is tender and dark green. However in 2-year-old culms, the darkened culm sheaths can only be observed on the 1st and 2nd internodes above ground and the culm skin is hardened and grayish-green. In 3-year-old culms, no sheaths can be observed, as they are fallen on the ground and have started rotting. The culm skin is yellowish-green with lichens growing on the surface. Internodes of each culm were consecutively numbered from bottom to top and were then divided into three portions, *i.e.* bottom, middle and top portions, each with equal number of internodes. Three internodes were identified from each portion (3rd for bottom, 8th for middle, and 15th for top portion) in culms of every age group. The identified internodes were cut and measured immediately for the fresh weight in the wild. This was done in order to avoid the errors in moisture content caused by the water loss of culm samples during transportation. After that, all samples were brought to the lab to measure dry weight for calculating moisture content, and then were chipped into strips (2 mm × 5 cm) with intact inner and outer skin for other measurements (Wang *et al*. 2011).

Methods

Determination of chemical properties

The internode strips for chemical analysis were oven dried at 60 °C for 24 h and then ground in a Wiley mill. The ground material was placed in a shaker. Particles that passed a no. 40 mesh sieve but were retained on no. 60 mesh were used for subsequent chemical analysis. Chemical analyses were conducted based on the standard methods from the Chinese National Standards for Testing and Materials, including Moisture-GB/T 1931-2009 (CNSTM 2009), Ash-GB/T 2677.3-93 (CNSTM 1993), Silicon dioxide (SiO_2)-GB/T 7978 (CNSTM 1987), Alcohol–toluene extractive- GB/T 10741-89 (CNSTM 1989), Lignin- GB/T 2677.8-94 (CNSTM 1994) & GB/T 10337-2008 (CNSTM 2008), and Holocellulose-GB/T 2677.10-1995 (CNSTM 1995). Each test was triplicated.

Determination of fiber properties

For measuring fiber dimensions, strip samples (2 mm × 5 cm) were put into a graduated test tube with a stopper, and then treated with Jeffery's solution (1:1 mixture ratio of 10% nitric acid and 10% chromic acid) for 36 to 72 h as suggested by Wilson (1954). A minimum of 150 intact and straight fibers from each sample, totaling 1,395 samples, were measured using a microscope (Phoenix PH100-3B41L-IPL,China) to obtain data for fiber length, width, wall thickness, and lumen diameter with objective lenses at 10x, 40x, 40x, and 40x, respectively.

Data analysis

The data from the experiments were statistically analyzed and compared by one-way ANOVA using the least significant difference method (LSD) to determine the level of significance at $P \leq 0.05$.

RESULTS AND DISCUSSION

Variation in Chemical Properties

The average relative proportions of the main chemical constituents measured for *F. fungosa* are moisture (50.87%), ash (1.94%), SiO_2 (0.39%), toluene-alcohol extractive (3.46%), acid-soluble lignin (1.67%), acid-insoluble lignin (21.82%), and holocellulose (70.22%).

Changes in initial moisture content with ages and heights

Moisture content (MC) is an important factor in determining the physical properties of bamboo. The MC of *F. fungosa* gradually decreased with increasing culm ages, reaching the lowest average of 46.62% at 3 years (Fig. 1 and Table 1). Jamaludin *et al.* (2002) found a similar trend in 1- to 3-year old *Gigantochloa scortechinii*. Norul Hisham *et al.* (2006) also reported that the lowest MC was observed in the oldest culm (6.5 years) of *G. scortechinii.* The MC decrease with the increasing culm age might be attributable to the correlation between culm lignification and anatomical structures, particularly the vascular bundles and parenchyma cell distribution. However, no specific trend was observed in MC with different culm height portions.

As revealed in numerous investigations, the MC of a culm is considerably higher at the base than at the top. This has been attributed to the different amount of parenchyma present (Liese and Grover 1961). The results showed that MC of bottom and middle portions were significantly higher than the top portions, due to the higher amount of parenchyma tissues. Tamolang *et al*. (1980), Jamaluddin (1999), and Anwar *et al*. (2005) also reported that MC decreases with the culm heights in the species studied. The lower MC at the top portion is associated with the decrease in the percentage of parenchyma cells and the higher concentration of vascular bundles distributed per unit area of culm wall thickness (Abd. Latif and Mohd Zin 1992; Abd. Latif and Mohd Tamizi 1992).

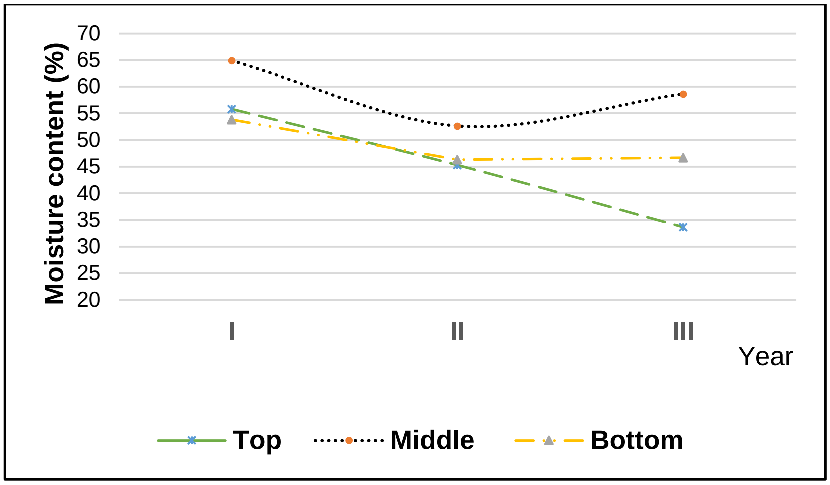

Fig. 1. Changes in moisture content of *Fargesia fungosa* with ages & heights

Changes in chemical composition with ages

Chemical compositions in 1, 2, and 3-year-old *F. fungosa* culms showed relatively minor differences (Table 1). Ash content decreased with increasing culm ages and was significantly higher in 1-year culms than that in 2 and 3-year culms, which agreed with the findings of Zhang *et al.* (2002) that the ash content in bamboo culms of *Phyllostachys edulis* decreased with age in the first five years of growth. However, Li *et al.* (2007) reported that ash content showed no significant difference in mature bamboo species of *Phyllostachys pubescens*. Similarly, SiO_2 content also decreased with increasing culm ages. Li *et al.* (2007) considered that the similar trend in ash and SiO_2 contents was due to the fact that the 1-year-old culms had higher proportions of silica-rich epidermal tissue and metabolically active vascular tissues, which mobilizes inorganic nutrients to other plant organs. Moreover, the MC in culms also affected the ash and SiO_2 contents. The high moisture and low dry weight of 1-year-old culms contributed to the high ash and SiO_2 contents as calculated.

Norul Hisham *et al*. (2006) reported no specific trend for toluene–alcohol extractives in the bamboo *G. scortechinii* at different ages. However, in *F. fungosa*, the toluene–alcohol extractives increased significantly with bamboo ages, reaching the highest average at 4.14% at 3 years. Li *et al.* (2007) also reported a similar trend in the extractive content and they considered that the increasing extractive content in bamboo is analogous to that in trees where extractives deposition can also increase with age and impart greater decay resistance.

Lignin content increased slightly with ages, but no specific trend for holocellulose was observed, which indicated the constant lignification in culms. Lin *et al.* (2002) reported that the lignification process of fiber and parenchyma cells can last even up to 7 years in *P. pubescens*. As for holocellulose, Abd. Latif *et al.* (1994) reported that there was no clear trend in 1- to 3-year old *G. scortechinii*, while Mohd Nor *et al.* (1992) considered the holocellulose, a-cellulose and lignin contents increased slightly from one to three years of age. Wang *et al.* (2011) also reported that lignin and holocellulose contents increased with age slightly.

The range of cellulose contents implies that bamboo can be regarded as a suitable raw material for the pulp and paper industry (Li *et al.* 2007). The lignin content (20 to 26%) also places bamboo at the high end of the normal range (11 to 27%) reported for nonwoody biomass and close to the ranges for North American softwoods (24 to 37%) and hard woods (17 to 30%) (Bagby *et al*. 1971; Li *et al*. 2007). The high lignin content in bamboo contributes to its structural rigidity, making it a valuable building material (Scurlock *et al*. 2000). High ash content for some bamboo species can adversely affect tool/knife wear during machining operations and processing into pulp (Abd. Latif 1993). Data from the lab tests in this study showed that the low lignin and ash contents, as well as high holocellulose content in 3-year-old culms of *F. fungosa* made it suitable for pulping and papermaking.

Table 1. Mean Values of Major Chemical Constituents of *Fargesia fungosa* from Different Portions and Ages

Age class	Position	Moisture	Ash	SiO_2	Toluene-alcohol extractive	Acid-soluble lignin	Acid-insoluble lignin	Lignin	Holo-cellulose
I	Top	55.81a	2.89a	0.53a	3.19a	1.60a	22.33a	23.93a	69.29a
	Middle	64.93a	2.94a	0.50a	2.97a	1.44a	18.30a	19.75a	70.93a
	Bottom	53.82a	2.80b	0.41b	2.86a	1.78a	22.52a	24.30a	69.88a
	Mean	58.18a	2.88a	0.48a	3.01a	1.61a	21.05a	22.66a	70.03a
II	Top	45.29a	1. 79a	0.48a	3.01a	1.70a	24.43a	26.13a	72.63a
	Middle	52.64b	1.39b	0.34b	3.05a	1.60a	21.23b	22.83b	69.66b
	Bottom	46.34ab	1. 35b	0.33b	3.60a	1.66a	22.01b	23.68b	70.00b
	Mean	48.09a	1.51b	0.38b	3.22a	1.65a	22.56a	24.21a	70.77a
III	Top	33.63a	1.16a	0.30a	5.61a	1.79a	22.13a	23.92a	69.76a
	Middle	58.64b	1.51b	0.34a	3.31b	1.76a	21.24a	23.00a	69.38a
	Bottom	46.69b	1.54b	0.25a	3.51b	1.66a	22.19a	23.29a	70.46a
	Mean	46.62a	1.40b	0.30c	4.14b	1.74a	21.86a	24.04a	69.86a
Mean	Top	44.91a	1.95a	0.43a	3.93a	1.70a	22.96a	24.66a	70.56a
	Middle	58.78b	1.96a	0.39ab	3.11a	1.60a	20.26b	21.86b	69.99a
	Bottom	48.95ab	1.90a	0.33b	3.32a	1.70a	22.24a	23.76a	70.11a
	Mean	50.87	1.94	0.39	3.46	1.67	21.82	23.42	70.22

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

Changes in chemical composition with heights

The chemical constituents of *F. fungosa* culms appeared to change with heights (Table 1). However, the differences were not significant. Ash and SiO_2 contents increased from bottom to top slightly, but toluene–alcohol extractives, lignin, and holocellulose contents did not demonstrate a specific trend with culm heights. They decreased with height in the beginning but presented a slightly rising trend towards the top portions. The lignin and holocellulose contents were the highest at the top of the culm mainly due to the increasing vascular bundle cells with secondary thickening and lignification. At the culm bottom, there were relatively more parenchyma tissues than at the top while the top had relatively higher vascular bundle concentrations. Therefore, the lignin and holocellulose contents on the top portion of the bamboo culm were relatively high, which was similar to that reported in *F. yunnanensis* by Wang *et al.* (2011).

Changes in fiber dimension

Fiber morphology has an important impact on the physical properties of pulp (Tamolang *et al.* 1967; Zamuco *et al.* 1969). Variability in fiber morphological characteristics in *F. fungosa* bamboo was apparent (Table 3).

It was observed that the fiber lengths of *F. fungosa* were in the range of 0.23 to 3.28 mm, and the mean value was 1.31 mm (Tables 2 and 3), which belonged to the range of middle and long fibers, according to the Items of the International Society for Wood Anatomy (Yang *et al.* 2008; Wang *et al.* 2008).

Table 2. Basic Fiber Index of *Fargesia fungosa*

	Length L (mm)	Width W(μm)	L/W	Wall thickness Wt (μm)	Lumen diameter Ld (μm)	Wt/Ld
Maximum	3.28	31.20	248.00	10.40	26.00	15.67
Minimum	0.23	5.20	29.33	1.30	0.78	0.18
Mean	1.31	13.58	102.45	4.31	4.95	3.43

Table 3. Fiber Characteristics of *Fargesia fungosa* at Different Ages and Portions

Age class	Position	Length mm	Width μm	L/W	Wall thickness μm	Lumen diameter μm	Wt/Ld
Ⅰ	Top	1.29a	13.58a	103.96a	3.54a	6.50a	2.35a
	Middle	1.22a	14.75a	90.07b	4.17b	6.41a	3.17b
	Bottom	1.25a	13.91a	97.66ab	3.20a	7.53a	2.00a
	Mean	1.25a	14.08a	97.25a	3.63a	6.81a	2.50a
Ⅱ	Top	1.42a	13.36a	111.28a	5.05a	3.26a	4.63a
	Middle	1.27b	14.30a	91.25b	4.86a	4.58b	3.61b
	Bottom	1.20b	12.01b	108.88a	3.62b	4.78b	3.14b
	Mean	1.30ab	13.21b	103.86b	4.50b	4.21b	3.79b
Ⅲ	Top	1.20a	12.92a	98.41a	4.57a	3.79a	4.20a
	Middle	1.51b	13.52a	116.99b	4.85ab	3.82a	3.94a
	Bottom	1.42b	13.77a	104.30a	5.14b	3.49a	4.06a
	Mean	1.37b	13.41ab	106.59b	4.86c	3.70b	4.07b
Means	Top	1.30a	13.29a	104.53a	4.36a	4.56a	3.69a
	Middle	1.33a	14.20b	99.29a	4.62a	4.97ab	3.56a
	Bottom	1.29a	13.24a	103.52a	3.97b	5.31b	3.04b
	Mean	1.31	13.58	102.45	4.31	4.95	3.43

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

Changes in fiber morphology with ages

Fiber length had significant impact on the tearing and tensile strength of the paper. The fiber length and length-to-width ratio of *F. fungosa* increased with ages, and the longest fibers were found in the 3-year culms (Table 3). The fiber length and length-to-width ratio in 1- and 2-year bamboo was significantly higher than those in 3-year culms.

However, the fiber width in different culm ages did not show an analogous rule; fiber width increased in the order of 1-year> 3-year> 2-year, and the difference between 1 and 2-year-old bamboo was significant. It was concluded that bamboo age had a significant impact on fiber length. No specific trend was observed with respect to fiber width. Wang *et al*. (2011) reported that the fibers of *F. yunnanensis* complete their length and width growth in one or two years. Norul Hisham (2006) observed that the fiber length increased from 0.5 years to 1.5 years and then decreased with ages in *Gigantochloa. scortechinii*. Nordahlia *et al*. (2012) reported that the 4-year-old culms had longer fiber length compared with 2-year-old culms in *G. levis*. It follows that external factors such as soil conditions and climatic changes during fiber development may influence fiber morphology (Nordahlia *et al*. 2012). In general, the fiber length-to-width 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 mean value of length-to-width ratio of *F. fungosa* is 102.45, showing good suitability for pulp raw material.

It was also noted that the fiber wall thickness of *F. fungosa* increased significantly with age and was thinner at the early age of 1 year (3.63μm) but had thickened by as much as 1.23 μm at 3 years (4.86 μm). Liese and Weiner (1996) as well as Murphy and Alvin (1997) reported a thicker fiber walls in older bamboos. When the maximal culm height is attained, the growth of fiber length and width halts, but fiber wall thickening continues for two to three years (Gan and Ding 2006, Wang *et al.* 2011). Fiber wall thickening is caused by the deposition of additional lamellae with age (Nordahlia *et al.* 2011).Wang *et al*. (2012) also reported that the 3-year-old culms still have lots of thin-walled fibers that continue thickening in subsequent growing years. However, Abd. Latif and Mohd Tamizi (1992) reported that fiber wall thickness in bamboo *G. scortechinii* was not affected by age. Therefore, whether fiber wall thickening performance is species-specific needs to be further studied.

The fiber lumen diameter decreased with culm ages, of which 1-year-bamboo was obviously higher. However, the wall/lumen ratio gradually increased with the culm ages. The widest mean fiber lumen diameter was observed in the youngest culm of 1-year age (6.81μm) whereas the largest wall/lumen ratio was observed in the 3-year culms.

Changes in fiber morphology with heights

The mean values of fiber length, width, and wall thickness of the bamboo culms did not show any specific trend with increasing culm heights. The fiber length varied slightly in the order of middle > top > bottom (Table 3). The middle and top internodes were longer than the bottom ones. Hence, they had longer fibers. Pu and Du (2003) reported that fibers in the bottom culms were longer than the middle and top ones in *Dendrocalamus sinicus*. A similar trend was also reported for *F. yunnanensis* by Wang *et al.* (2011), who found that fiber length varied with portions and the middle portions had the longest fibers.

The anatomical properties such as fiber length affect the strength properties of paper (Wangaard and Woodson 1973). When selecting bamboo species for papermaking, the impact of the internodal lengths on the fiber length needs to be taken into consideration. The fiber width increased from the bottom to the middle portions, but decreased towards the top portions. Meanwhile, the fiber from the middle portion had significantly higher width than that of the top and bottom portions. The fiber length-to-width ratio was somewhat greater at both bottom and top than the middle ones.

The mean of fiber wall thickness of the middle portion was the greatest. The greatest fiber wall thickness of *F. fungosa* was observed in the bottom portion of the 3-year culm (5.14 μm). However, the minimal values were observed at the bottom of the 1-year-old culms (3.20 μm). The fiber thickening increased with culm heights in the early growth stage may be closely related to the increasing density of bamboo material, which benefits bamboo stems in resisting damages from external force (Gan and Ding 2006). The lumen diameter decreased from the bottom to the top portions, but the wall-to-lumen ratio presented an opposite trend. Fiber wall-to-lumen ratio, or Runkel ratio, is taken as one of the criteria for assessing the suitability of fibrous materials for the paper industry (Wu 1997; Wang *et al.* 2008). Runkel reported that a fiber wall to lumen ratio below 1 is fine fiber raw material, greater than 1 is inferior, and equal to 1 is the secondary fiber raw material (Wu 1997). The mean of the fiber wall to lumen ratio of *F. fungosa* is 3.43; therefore, it belongs to inferior raw material for papermaking.

CONCLUSIONS

1. The chemical properties of *F. fungosa* differed with ages and heights. The initial MC gradually decreased with increasing culm ages, but no specific trend was observed in different height portions. The variation of *F. fungosa* culms in ash, SiO_2 contents, and toluene–alcohol extractive with culm ages was greater than those with heights. The holocellulose varied significantly with neither age nor height.
2. The fiber morphology of *F. fungosa* differed with ages and heights. The fiber length, width, length-to-width ratio, and wall thickness increased with culm ages. However, there was no specific trend in different height portions. The mean average of lumen diameter decreased with increasing bamboo ages and heights, in which the bottom portion of 1-year bamboo had the highest average. In contrast, the wall-to-lumen ratio increased with increasing bamboo ages and heights, in which the top portion of the 2-year growth bamboo reached the highest.
3. The 3-year-old culms of *F. fungosa* are suitable for pulp and papermaking based on their fine chemical properties and fiber morphology.

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