

Fiber morphological characteristics of bamboo *Ferrocabamus strictus* culms from different geographical distribution regions

Xiaofeng Zheng

Southwest University

Rui Xu

Southwest Forestry University

Ziteng Zhou

Southwest Forestry University

Jiamin Wang

Southwest Forestry University

Hui Zhan

Southwest Forestry University

Changming Wang (✉ forestwcm@swfu.edu.cn)

Southwest Forestry University

Research Article

Keywords: *Ferrocabamus strictus*, Fiber morphology, Soil elements

Posted Date: November 14th, 2023

DOI: <https://doi.org/10.21203/rs.3.rs-3582094/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Abstract

The fiber index including fiber length, width, wall thickness and lumen diameter of *Ferrocalamus strictus* culms (1, 2, and ≥ 3 years) from Jinping, Mojiang and Lvchun counties of Yunnan Province was determined and the elemental content of the soil was also determined to analyze the influence of the culm age and height and soil content on the fiber characteristics. The average relative fiber index measured for *F. strictus* culms were fiber length (1.30 mm), width (21.57 μm), slenderness ratio (60.79 μm), wall thickness (4.21 μm), lumen diameter (7.22 μm), and runkel ratio (1.22 μm), which belonged to the range of middle and long fibers. The fiber length increased with the culm age. The proportion of long fiber increased while short fibers decreased along with culm maturing. The fiber morphology did not show a specific trend with the culm height. Fiber length reached the maximum in the bottom portions of the culms. There is a correlation between fiber morphology and soil elements, the content of organic matter, total potassium, total sulfur, total aluminum, total zinc, total iron, total boron, alkali-hydrolyzed nitrogen and available silicon in the soil affects fiber morphology. The content of organic matter, total boron, available potassium and alkali-hydrolyzed nitrogen in the soil from Mojiang County was largest. Comparatively, the culm fiber in Mojiang County had the best fiber index performance for utilization, since the greatest proportion of medium and long fibers and the optimal distribution of fiber length frequency was obtained from the culms in Mojiang County. This study can provide a theoretical basis for large-scale bamboo forest cultivation and the development and utilization of bamboo culm fiber.

1 Introduction

Bamboo is considered to be an important type of forest resource with long fiber length, rapid growth and excellent timber properties (Ogunwusi et al. 2022). China is rich in bamboo resources, with a total of 941 species in 43 genera, nearly 50% of which are distributed in Yunnan Province (Xu et al. 2023). With the overextraction of timber resources, the conflict between supply and demand continues to aggravate, the expansion of bamboo plantations for pulp and papermaking (Cai et al. 2020), furniture decoration (Raydan et al. 2021), artificial composite boards (Fu et al. 2012) and fiber textiles (Lian et al. 2022) provides an alternative solution.

Ferrocalamus strictus is a type species of *Ferrocalamus* in the subfamily Bambusoideae. It was discovered by Bojie Geng and Jiru Xue in 1982 and named for its hard culm (Geng et al. 1982; Li et al. 2015). It is one medium-sized monopodial bamboo (Yu et al. 2018), with the internode length above 100 cm, which is a good material for making chopsticks and woolen needles (Geng et al. 1982; Li et al. 2015). At present, *F. strictus* is known to be distributed only in Honghe and Pu'er prefectures in Yunnan Province of China. It was listed as one of the very small population species in Yunnan Province in 2007 due to the characteristics of narrow distribution and sparse population (Li et al. 2015), and listed as a China key national first-class protected wild plant in 2021 (Kou, 2021).

Research on bamboo fiber morphology provides a basis for the cultivation, processing and utilization of bamboo. Bamboo fiber morphology exhibits anisotropy. Analyzing the anisotropy of bamboo fiber

morphology can achieve reasonable utilization for bamboo resources. Wang et al. (2009) and Niu et al. (2023) found that the culm age and different portions had a significant effect on the fiber morphology of *Fargesia yunnanensis* and *Phyllostachys edulis*. Li et al. (2010) analyzed the fiber morphological characteristics of *Oxytenanthera abyssinica* and concluded that the maximum utilization of bamboo can achieve by considering harvesting age and portion. Chen et al. (2015) found that the different ages and parts of sympodial bamboo culms had their own advantages and disadvantages in papermaking performance. In addition, bamboo fiber can also be used in board processing and product packaging and other fields. The research of Meng et al. (2011) showed that under different experimental conditions, fibrous bamboo reconstituted board has excellent physical and chemical properties and can be promoted for production. Delgado et al. (2012) analyzed the availability of bamboo fiber composites in product packaging. Zhan et al. (2022) studied the fiber morphological characteristics of culm sheaths of different bamboo species, indicating that the sheaths could be used for papermaking, which improved the availability of unconventional raw materials. *F. strictus* is the bamboo species with the longest and hardest internodes reported in the world, however, there is no report on the morphological characteristics of its fiber and its potential for large-scale industrial utilization has yet to be further explored.

Accordingly, this study endeavors to analyze the fiber morphological characteristics of *F. strictus* culms of different ages from different geographical distribution regions to explore the morphological variation of *F. strictus* fiber to provide a theoretical reference for its economic and germplasm value.

2 Materials and methods

2.1 Materials

Materials were collected from three geographical distribution areas of *F. strictus* in Yunnan Province (Table 1). eg, Huotandong Village in Jinping County (JP), Lazhu Village in Mojiang County (MJ) and Taihong Village in Lvchun County (LC).

Table 1
Sampling locations

Location			
	JP	MJ	LC
Longitude	E103°2'27.6"	E101°50'22.3"	E102°27'52.2"
Latitude	N22°36'45.4"	N22°57'14"	N22°50'9.28"
Altitude (m)	1380	1720	1180
Climate type	Tropical monsoon climate	Subtropical monsoon climate	Subtropical mountain monsoon climate
Average annual temperature (°C)	18	17.8	16.6
Average daily maximum temperature (°C)	22	26	23
Average daily minimum temperature (°C)	15	14	15
Average annual rainfall (mm)	2330	1345	2400
Annual sunlight duration (h)	1680	2160	1368

Sampling was referred to the method from Xu et al. (2023). Three bamboo culms of *F. strictus* from three distribution areas in each of the three age groups (1, 2, and ≥ 3 years old) were cutted. Three samples of each age group totaling 27 culms were used for replication. The culm internodes were consecutively numbered from bottom to top and then divided into three portions, each with an equal number of internodes, i.e., 1st for bottom, 4th for middle and 7th for top portion.

Soil collection was referred to the method from Wang et al. (2022).

Culm samples were cleaned with pure water and then cleaned again with an ultrasonic cleaner to ensure the removal of debris. Then culm samples were dried in an oven at 80°C and cool in a drying basin for 12 hours. The soil was cleared of debris and passed the screens for 400 mesh and 200 mesh sieves.

2.2 Methods

Referring to the segregation method of Zhang et al. (2007), the fibers of *F. strictus* culm were obtained (Fig. 1). Slides were made, more than 50 photos were taken of each slide, and the basic index of length, width, wall thickness, lumen diameter of the fiber were determined using the Image - J measurement software. Two derived values were calculated according to the fiber dimensions measured (Slenderness ratio (fiber length/fiber width) and Runkel ratio $[(2 \times \text{fiber cell wall thickness}) / \text{fiber lumen diameter}]$). The

soil element content determination refers to the China Forestry Industry Standard, LY/T 1270–1999 (CFIS 1999). SPSS26.0 and Origin2021 software were used for data analysis.

3 Results

3.1 Fiber morphology

The mean fiber length of *F. strictus* from three distribution areas was 1.30 mm, the mean width was 21.57 μm , the mean slenderness ratio was 60.79 μm , the mean wall thickness was 4.21 μm , the mean lumen diameter was 7.22 μm , and the runkel ratio was 1.22 μm .

3.1.1 Morphological characteristics of culm fiber in different locations

Fibers of *F. strictus* culms from different locations had different performance in terms of fiber characteristics (Fig. 2). The average fiber length in MJ was significantly larger than that in JP and LC. The average fiber width was decreased in the order of MJ > LC > JP, and significant differences was observed among the three locations. The mean of fiber slenderness ratio was the greatest in LC (62.54 μm) with insignificant difference among different locations. The mean wall thickness and runkel ratio was the greatest in MJ. However the lumen diameter of the culm in MJ was the smallest. The wall thickness of the MJ was significantly larger than that of JP and LC. The lumen diameter of the JP was larger than that of the MJ. The runkel ratio of the MJ was larger than that of the JP and LC. (Table 2).

In JP, the fiber length, width, slenderness ratio and wall thickness of 3-year culms was larger than that of 1- and 2-year culms. The wall thickness of 3-year culms was significantly larger than that of 1-year culms. However, insignificant difference in fiber length was observed among different portions of the culm (Fig. 3). The lumen diameter of the bottom portion of the culm was significantly greater than the middle portions.

In MJ, the greatest fiber length and slenderness ratio was found in 2-year culms. 3-year culms had greater width and lumen diameter than that of 1- and 2-year culms. The wall thickness and runkel ratio of 2-year culms was larger than that of 2- and 3-year culms. (Fig. 3) The middle portions had significantly larger the width than the top and bottom portions. No significant difference in length, slenderness ratio, wall thickness, lumen diameter and runkel ratio were observed among different portions of the culm (Fig. 2).

In LC, 3-year culms was the longest fibers. The width of 1- and 2-year culms was significantly greater than that of 3-year culms, whereas the smallest slenderness ratio was observed in 1-year culms. The fiber slenderness ratio presented a decreasing trend with increasing culm ages (Fig. 3). The bottom portion had greater fiber length and lumen diameter than the top and middle portions. No significant differences in the width, slenderness ratio, wall thickness and runkel ratio were observed among different culm portions (Fig. 2).

3.1.2 Morphological characteristics of culm fibers in different ages

The fiber wall thickness in *F. strictus* culm increased with the culm age and reached the maximum values in 3-year culm (Table 2). For 1-year culm, the fiber length, width, slenderness ratio, wall thickness, lumen diameter and runkel ratio was the largest in MJ, while the fiber slenderness ratio of the 2-year culms was the smallest in MJ. The fiber length, width, slenderness ratio and lumen diameter were the smallest in 1-year culms. Significant differences in wall thickness was observed among different 1- and 3-year culms, the fiber wall thickness of 3-year culms was larger than that of 1-year culms (Fig. 2).

Table 2
Fiber morphology of bamboo culm in different locations, ages and portions

		Length (mm)	Width (μm)	Slenderness Ratio (L/W)	Wall thickness (μm)	Lumen diameter (μm)	Runkel Ratio (2Wt/Ld)
Location	JP	1.08 $\pm$ 0.05b	18.57 $\pm$ 0.48b	58.11 $\pm$ 1.73a	3.95 $\pm$ 0.18b	8.16 $\pm$ 0.50a	1.00 $\pm$ 0.07b
	MJ	1.45 $\pm$ 0.05a	23.49 $\pm$ 0.81a	62.00 $\pm$ 2.46a	4.93 $\pm$ 0.17a	6.11 $\pm$ 0.15b	1.62 $\pm$ 0.06a
	LC	1.36 $\pm$ 0.04a	21.80 $\pm$ 0.67a	62.54 $\pm$ 1.99a	3.74 $\pm$ 0.15b	7.38 $\pm$ 0.62ab	1.05 $\pm$ 0.06b
Age	1	1.31 $\pm$ 0.09a	21.50 $\pm$ 1.17a	60.55 $\pm$ 2.47a	3.96 $\pm$ 0.22a	7.40 $\pm$ 0.61a	1.14 $\pm$ 0.11a
	2	1.23 $\pm$ 0.05a	20.92 $\pm$ 0.82a	58.98 $\pm$ 2.11a	4.24 $\pm$ 0.27a	6.54 $\pm$ 0.47a	1.33 $\pm$ 0.11a
	3	1.38 $\pm$ 0.06a	22.31 $\pm$ 0.89a	61.79 $\pm$ 1.58a	4.42 $\pm$ 0.23a	7.71 $\pm$ 0.49a	1.20 $\pm$ 0.12a
Position	Top	1.27 $\pm$ 0.07a	21.48 $\pm$ 0.94a	59.02 $\pm$ 1.38a	3.97 $\pm$ 0.21a	6.86 $\pm$ 0.49a	1.21 $\pm$ 0.11a
	Middle	1.31 $\pm$ 0.07a	22.27 $\pm$ 0.98a	58.81 $\pm$ 1.57a	4.26 $\pm$ 0.25a	6.87 $\pm$ 0.46a	1.28 $\pm$ 0.11a
	Bottom	1.33 $\pm$ 0.08a	20.98 $\pm$ 1.00a	63.49 $\pm$ 2.72a	4.40 $\pm$ 0.25a	7.93 $\pm$ 0.61a	1.18 $\pm$ 0.13a
Mean		1.30 $\pm$ 0.01	21.57 $\pm$ 0.18	60.79 $\pm$ 0.59	4.21 $\pm$ 0.14	7.22 $\pm$ 0.31	1.22 $\pm$ 0.07

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

For the 1-year culms, the value of fiber morphology were the largest in the MJ. The value of fiber morphology were the smallest in the JP (Fig. 3). The fiber length and width of MJ and LC was larger than that of JP. The fiber runkel ratio of MJ and JP was larger than that of LC. No significant differences in the slenderness ratio, wall thickness and lumen diameter were observed among different locations.

For the 2-year culms, the fiber length of the MJ and LC had significantly larger than that of the JP. The fiber width, wall thickness and runkel ratio of the MJ were significantly larger than that of the JP and LC. The slenderness ratio of the LC was largest and the lumen diameter of the JP was largest (Fig. 3).

In the 3-year culms, the fiber length of JP had significantly smaller fiber length than the MJ and LC. The fiber width of culm had significant difference in locations and the fiber width of the MJ was largest. The LC had significantly smaller fiber wall thickness than the MJ. The JP and LC had significantly smaller runkel ratio than the MJ. No significant differences in the slenderness ratio and lumen diameter were observed among different locations.

3.1.3 Morphological characteristics of culm fiber in different portions

The fiber length, slenderness ratio, wall thickness and lumen diameter average in bottom portions of *F. strictus* culm showed the greatest, the fiber width and runkel ratio average in middle portions of *F. strictus* culm showed the greatest (Table 2). The slenderness ratio was increased in the order of bottom portions > middle portions > top portions. The lumen diameter in bottom portions of JP had significantly larger than that in middle portions of JP. The width in middle portions of MJ had significantly larger than that in bottom portions of MJ (Fig. 2). No significant difference in fiber length, slenderness ratio, wall thickness and runkel ratio were observed among different portions of the culm.

For the top portion of the culms, the fiber length, width and runkel ratio of MJ had significantly larger than that of JP. The lumen diameter of JP had significantly larger than that of MJ. No significant difference in the slenderness ratio and wall thickness were observed among different portions of the culm.

For the middle portion of the culms, the fiber length of MJ had significantly larger than that of JP, the fiber width was significant difference in the order of MJ > LC > JP, the wall thickness of MJ had significantly larger than that of JP and LC, the runkel ratio was significant difference in the order of MJ > JP > LC. No significant difference in the slenderness ratio and lumen diameter were observed among different locations.

For the bottom portion of the culms, the fiber length of MJ and LC had significantly larger than that of JP, the fiber width of MJ had significantly larger than that of JP and LC, the lumen diameter of JP had significantly larger than that of MJ, the runkel ratio of MJ had significantly larger than that of JP and LC. No significant difference in the slenderness ratio and wall thickness were observed among different locations.

3.1.4 Frequency distribution of the mean fiber length

According to the classification standards of the International Council of Wood Anatomy, the length of short fiber is below 0.9 mm, medium fiber is in the range of 0.9 mm and 1.6mm, and long fiber is above 1.6 mm (Li et al. 2017). The proportion of long and medium fibers were larger in *F. strictus* culm, the proportion mean of long fiber was 23%, the medium fiber was 59.5% and the short fiber was 17.5%. The frequency distribution of fiber length of *F. strictus* culm varied greatly between locations, ages and portions. The proportion of long fiber was the highest in MJ (36.6%), followed by LC (23.0%) and JP (10.0%), while JP had the highest proportion of short fiber. The medium fibers demonstrated an increasing trend with culm ages, and the proportion of long fibers reaches its maximum in 3-year culms. The proportion of long and medium fibers in the middle portion of the culm was greater than that in the top and bottom portions (Table 3).

Table 3

Frequency distribution of fiber length of *Ferocalamus strictus* culm in locations, ages and positions

Fiber Length (mm)	Location (%)			Age (%)			Portion (%)			Mean (%)
	JP	MJ	LC	1	2	3	Top	Middle	Bottom	
$L \leq 0.9$	34.6	6.4	10.7	20.0	20.4	11.2	20.4	14.6	19.6	17.5
$0.9 \leq L \leq 1.6$	55.4	57	66.3	55.9	62.1	60.7	59.3	61.3	57.4	59.5
$1.6 \leq L$	10	36.6	23	24.1	17.5	28.1	20.3	24.1	23.0	23.0

3.2 Soil elemental in different locations

The content of organic matter, total boron, available potassium and alkali-hydrolyzed nitrogen in the soil from MJ was largest than those in JP and LC. The organic matter content in the soil from MJ ($109.57 \text{ g} \cdot \text{kg}^{-1}$) was significantly higher than that from JP ($59.51 \text{ g} \cdot \text{kg}^{-1}$), the total boron content in the soil of MJ ($26.50 \text{ mg} \cdot \text{kg}^{-1}$) and LC ($23.6 \text{ mg} \cdot \text{kg}^{-1}$) were significantly higher than that in JP ($6.10 \text{ mg} \cdot \text{kg}^{-1}$), and the alkali-hydrolyzed nitrogen content in MJ ($271.00 \text{ mg} \cdot \text{kg}^{-1}$) and LC ($260.00 \text{ mg} \cdot \text{kg}^{-1}$) was significantly greater than that in JP ($200.67 \text{ mg} \cdot \text{kg}^{-1}$) (Table 4).

The contents of total phosphorus, total sulfur, total calcium, total copper, total aluminum available potassium and available phosphorus in the soil from LC was largest (Table 4). The total phosphorus content in the soil from JP ($0.53 \text{ g} \cdot \text{kg}^{-1}$) and MJ ($0.56 \text{ g} \cdot \text{kg}^{-1}$) was significantly smaller than that in LC ($1.52 \text{ g} \cdot \text{kg}^{-1}$). The soil from LC had higher total sulfur content ($0.57 \text{ g} \cdot \text{kg}^{-1}$) than JP ($0.40 \text{ g} \cdot \text{kg}^{-1}$). The content of total calcium, total copper, available potassium and available phosphorus was the greatest in the soil from LC but lowest in JP. The total potassium content showed the regularity in the soil, followed by JP ($35.64 \text{ g} \cdot \text{kg}^{-1}$), LC ($22.37 \text{ g} \cdot \text{kg}^{-1}$), MJ ($7.96 \text{ g} \cdot \text{kg}^{-1}$). The total magnesium, total iron, total zinc content showed the regularity in the soil, followed by LC, JP, MJ. (Table 4).

Table 4
Differences in soil elements in locations

Element	Location			Mean
	JP	MJ	LC	
O. M(g·kg ⁻¹)	59.51 ± 2.25B	109.57 ± 15.54A	70.96 ± 3.53AB	84.30 ± 10.35
T.K(g·kg ⁻¹)	35.64 ± 0.89A	7.96 ± 0.59C	22.37 ± 0.13B	20.39 ± 4.30
T.P(g·kg ⁻¹)	0.53 ± 0.02B	0.56 ± 0.01B	1.52 ± 0.17A	0.77 ± 0.15
T.Mg(g·kg ⁻¹)	3.30 ± 0.11B	1.16 ± 0.08C	5.57 ± 0.33A	2.85 ± 0.61
T.S(g·kg ⁻¹)	0.40 ± 0.01B	0.49 ± 0.02AB	0.57 ± 0.06A	0.47 ± 0.03
T.Fe(g·kg ⁻¹)	27.08 ± 0.86B	23.00 ± 0.88C	42.84 ± 0.37A	28.77 ± 2.77
T.Mn(mg·kg ⁻¹)	185.67 ± 4.98B	159.75 ± 5.04B	1022.00 ± 78.00A	360.00 ± 125.87
T.Zn(mg·kg ⁻¹)	83.33 ± 1.76B	37.00 ± 11.03C	120.00 ± 1.00A	70.89 ± 12.56
T.Al(g·kg ⁻¹)	95.10 ± 1.67A	41.18 ± 2.69C	80.96 ± 0.75B	67.99 ± 8.76
T.Ca(g·kg ⁻¹)	0.34 ± 0.03B	0.38 ± 0.04B	6.71 ± 2.49A	1.77 ± 1.02
T.Cu(mg·kg ⁻¹)	7.10 ± 0.85B	8.68 ± 1.37B	45.80 ± 1.30A	16.40 ± 5.60
T.B(mg·kg ⁻¹)	6.10 ± 0.90B	26.53 ± 1.66A	23.60 ± 3.10A	19.07 ± 3.39
Hy.N(mg·kg ⁻¹)	200.67 ± 9.68B	271.00 ± 16.91A	260.00 ± 2.00A	245.11 ± 13.46
A.K(mg·kg ⁻¹)	112.00 ± 15.53B	143.75 ± 13.12AB	195.50 ± 11.50A	144.67 ± 12.99
A.P(mg·kg ⁻¹)	2.26 ± 0.40C	6.87 ± 0.94B	12.70 ± 2.23A	6.63 ± 1.46
A.Si(mg·kg ⁻¹)	65.00 ± 3.06B	24.50 ± 2.99B	156.50 ± 52.50A	67.33 ± 20.05
Note: O.M = Organic matter; T.K = Total potassium; T.P = Total phosphorus; T.Mg = Total magnesium; T.S = Total sulfur; T.Fe = Total iron; T.Mn = Total aluminum; T.Zn = Total zinc; T.Al = Total aluminum; T.Ca = Total calcium; T.Cu = Total copper; T.B = Total boron; Hy.N = Alkali-hydrolyzed nitrogen; A.K = Available potassium; A.P = Available phosphorus; A.Si = Available silicon.				

3.3 Correlation between fiber morphology and soil elements

There were correlation between fiber morphological of *F. strictus* culms and the soil elements content. The fiber slenderness ratio mean of *F. strictus* culms was positively correlated with the total sulfur content ($P < 0.05$) (Fig. 4). In the 1-year culm, the fiber width was significant positively correlated with the

content of total boron and alkali-hydrolyzed nitrogen in soil ($P < 0.05$). The slenderness ratio was extremely significant positively correlated with organic matter content ($P < 0.01$) and significant negatively correlated with the content of the total aluminum ($P < 0.05$). The wall thickness was significant negatively correlated with the content of the total potassium ($P < 0.05$). In the 2-year culms, a extremely significant positive correlation was observed between the fiber width and organic matter content ($P < 0.01$) and a significant negative correlation with total aluminum content ($P < 0.05$). The wall thickness was significant negatively correlated with the content of the total zinc ($P < 0.05$). In the 3-year culms, the fiber length was significantly positively correlated with the content of total nitrogen and alkali-hydrolyzed nitrogen ($P < 0.05$) and extremely significant positively correlated with the total boron content ($P < 0.01$). The fiber slenderness ratio was significantly positively correlated with total iron and available silicon content ($P < 0.05$), the wall thickness was significantly negatively correlated with the content of total zinc ($P < 0.05$).

4 Discussion

4.1 Fiber morphology

Analysis of the fiber morphology of *F. strictus* culms in different locations showed that the fiber morphology of culm in MJ was more stable. The maximum fiber index including fiber length, width, slenderness ratio, wall thickness and runkel ratio was obtained in the 1-year culms in MJ. This was inconsistent with the conclusions of Zhan et al. (2016), who studied the morphological characteristics of *Dendrocalamus hamiltonii* culm fibers and concluded that the fiber length and fiber slenderness ratio reached the maximum in the 2-year culms average. This was probably due to the fact that bamboo properties were characterized by its individual characteristics (Liese, 1985). This study found that the altitude, daily temperature difference, average annual sunshine duration and organic matter content were the largest in MJ were the highest among three geographical distribution regions of *F. strictus*. While other regions were adjacent to residential areas. Further research was needed to determine whether these factors affect the morphology of *F. strictus* culm fibers.

Generally, the slenderness ratio for good pulp raw materials needs to be larger than 30 (Gao et al. 2010). The mean slenderness ratio of *F. strictus* culms in different locations was above 30, showing good suitability for pulp raw material.

The average fiber length of *F. strictus* culm was in the range of 1.29 ~ 1.31 mm, the proportion of long and medium fibers were larger in *F. strictus* culm, which could be considered as pulping raw material for paper (Jing et al. 2022; Yusuf et al. 2018). The proportion of medium fiber and long fiber was large in the middle portion of *F. strictus* culms, this was consistent with the conclusion that most bamboo species have the best fiber morphology in the middle bamboo culm (Cao, 2022; Mayowa et al. 2016), the fiber slenderness ratio of *F. strictus* culm was close to that of *Melocalamus compactiflorus*, *Bambusa blumeana*, *Schizostachyum funghomii* and *Bambusa vulgaris* (Wang, et al., 2008), and the fiber length, width, wall thickness and runkel ratio were smaller, but the lumen diameter was larger. The larger the fiber

length, the greater the tear degree of the paper, and the smaller the runkel ratio improves the interweaving performance of the fiber, the *F. strictus* of culms can be a high-quality papermaking raw material. But the fiber runkel ratio was taken as one of the criteria for assessing the suitability of fibrous materials for the paper industry. The runkel ratio below 1 is fine fiber raw material, greater than 1 was inferior, and equal to 1 was the secondary fiber raw material (Wang et al. 2008). So papermaking also needs to consider multiple fiber morphological indicators in *F. strictus* of culms.

4.2 Soil elemental in different locations

The content of soil elements varied in different geographical distribution regions of *F. strictus*, and some elements showed significant differences, possibly due to plant distribution (Wyszkowski et al. 2016), climate (Zupancic et al. 2017) and even human production activities (Ivani et al. 2021) in different regions. The variation of soil element content may cause changes in fiber morphology of *F. strictus* culm in different regions. The content of organic matter, total nitrogen, boron, silicon and hydrolytic nitrogen in soil was the highest in MJ, which may support the stability of fiber morphology of *F. strictus* culm in MJ. The content of soil elements in MJ can be used as a reference for bamboo forest cultivation.

4.3 Correlation between the fiber morphology and soil elements

In this study, the contents of organic matter, total nitrogen and alkali-hydrolyzed nitrogen were the highest in MJ, and the length, width, wall thickness and runkel ratio of culm fibers were the highest in MJ. The correlation analysis between the morphology of *F. strictus* culm fibers and soil elements content found the fiber slenderness ratio mean was significant positively correlated with the total sulfur content, no significant correlation in the others fibers morphology and the soil elements content. In ages, an increase in organic matter content might be beneficial for the increase in width and slenderness ratio of the *F. strictus* fiber, while a high total aluminum content might hinder the change in fiber width and slenderness ratio. Wu et al. (2023) and Zhang et al. (2021) suggested that soil elements promote or inhibit each other, and their positive correlation indicated that there may be similar input sources for elements. Elements that were positively correlated with fiber morphology could be considered for the cultivation of bamboo forest, and elements that negatively correlated with fiber morphology could be regulated, which can conduct further research on the cultivation management and development and utilization of bamboo with high-quality fibers.

In order to increase the proportion of medium and long fibers, the *F. strictus* of 1-year can be supplemented with organic fertilizer in an appropriate amount, and the 3-year bamboo can be applied with nitrogen and boron. The fiber morphology index was minimum at 2-year culms, and the total aluminum content may have an antagonistic effect on it. The fiber length increased with *F. strictus* culm age, reaching its maximum at 3 year, and was significantly positively correlated with the contents of total boron and alkali-hydrolyzed nitrogen. The increase in fiber length may increase the demand for nitrogen, which was consistent with the research from Bai et al. (2016) that the growth of moso bamboo forest required a large amount of nitrogen. The *F. strictus* culm fiber showed a widening trend in the 1-year

culms, which might be positively affected by boron and nitrogen, as the fiber width was significantly positively correlated with total boron and alkali-hydrolyzed nitrogen content. In the 2-year culms, the fiber widening rate might decrease due to the inhibition of aluminum, as the fiber width was significantly negatively correlated with total aluminum content. In the 3-year culms, the widening trend of fiber width was not obvious, which may be due to the different elements absorbed by *F. strictus* at different growth stages, this was consistent with the conclusion from Liu et al. (2010) that the content of nitrogen, phosphorus, calcium, magnesium and other elements in bamboo culms varied with the increase of bamboo age.

5 Conclusion

The average relative fiber index measured for *F. strictus* culms were fiber length (1.30 mm), width (21.57 μm), slenderness ratio (60.79 μm), wall thickness (4.21 μm), lumen diameter (7.22 μm), and runkel ratio (1.22 μm), which belonged to the range of middle and long fibers. The fiber index of *F. strictus* varied with culm age, height and also geographical distribution regions. The fiber length increased with the culm age. The proportion of long fiber increased while short fibers decreased along with culm maturing. The fiber morphology did not show a specific trend with the culm height. The fiber length reached the maximum in the bottom portions of the culms.

The organic matter was applied to the *F. strictus* of 1-year, and nitrogen and boron fertilizers were applied to the *F. strictus* of 3-year to obtain medium and long fibers. There is a correlation between fiber morphology and soil elements, the content of organic matter, total potassium, total sulfur, total aluminum, total zinc, total iron, total boron, alkali-hydrolyzed nitrogen and available silicon in the soil affects fiber morphology. The content of organic matter, total boron, available potassium and alkali-hydrolyzed nitrogen in the soil from MJ was largest.

In comparison, the fiber index of MJ was the best application, since the greatest proportion of medium and long fibers and the optimal distribution of fiber length frequency was obtained from the culms in MJ.

Declarations

Author contributions

Xiaofeng Zheng completed the writing of this work; Rui Xu completed the Ideation and revision of this work; Xiaofeng Zheng, Ziteng Zhou and Jiamin Wang contributed equally to this work of the data processing; Hui Zhan and Changming Wang contributed equally to this work of revise. All author reviewed the manuscript.

Funding

This work was jointly funded by Yunnan Provincial Department of Education Foundation (No. 2022Y604); Yunnan Provincial Joint Special Project for Basic Research in Agriculture (202101BD070001-114);

National Natural Science Foundation of China (NO. 32160415); Natural Science Foundation of Yunnan Province (NO. 202001AT070108) and Xingdian Talent Support Plan Project (2022).

Competing interests

None.

References

1. Ogunwusi, A.A., Ibrahim, H.D. (2022). "Advances the in utilization of bamboo for paper production and the implication for countries with bamboo resources," *Journal of Resources Development and Management* 83, 18-26. DOI: 10.7176/JRDM/83-03
2. Zhan, H., Zhang, L.Y., Niu, Z.H., Wang, C.M., Wang, S.G. (2015). "Chemical properties and fiber morphology of *Dendrocalamus hamiltonii* as potential pulp material," *European Journal of Wood and Wood Products* 74(2), 273-276. DOI: 10.1007/s00107-015-0993-y
3. Wang, G., Cheng, H.T., Gu, S.H., Wang, C.C., Zhang, W.F. (2018). "Classification and application status of bamboo special shaped material," *Forest products industry* 45(11), 1-5. DOI: 10.19531/j.issn1001-5299.201811001
4. Cai, S.X., Xia,Y., Xu, B.J., Guo, Y.L. (2020). "Research on mechanical properties and design improvement of small diameter grade round bamboo furniture materials," *China Forest Products Industry* 57(09), 32-36. DOI: 10.19531/j.issn1001-5299.202009008
5. Raydan, N.D., Leroyer, L., Robles, E. (2021). "Recent advances on the development of protein-based adhesives for wood composite materials-a review," *Molecules* 26(24), 7617. DOI: 10.3390/molecules26247617
6. Fu, J.J., Li, X.Q., Silva, C. (2012). "Bio-processing of bamboo fibres for textile applications: a mini review," *Biocatalysis and Biotransformation* 30(1), 141-153. DOI: 10.3109/10242422.2012.650450
7. Lian, C.P., Wang, X.H., Chen, H., Fei, B.H., Pang, X.R., Lian, J.P., Wu, Z.H. (2022). "Using statistical methods to comparatively analyze the visual characteristics of flattened bamboo boards in different bamboo culm," *Polymers* 14(20), 4327. <https://doi.org/10.3390/polym14204327>
8. Geng, B.J., Xue, J.R. (1982). "Ferocalamus strictus genus - a new genus of bamboo in China," *Journal of Bamboo Research* 1(2), 1-5. <https://kns.cnki.net/kcms/detail/detail.aspx?dbname=CJFD1982&filename=ZZYJ198202000&dbcode=CJFD>
9. Li, E.L., Zhou J., Du, F., Hou, Z.Q., Bureau, M.F. (2015). "Discovery of wild ferocalamus strictus community in Mojiang County," *Forest Inventory and Planning* 40(04), 55-56. DOI: 10. 3969 / j. issn. 1671-3168. 2015. 04. 011
10. Yu D.X., Du F., Shi, M., Yang, C., Dai, J. (2018). "Community characteristics and population structure of *Ferocalamus strictus*, a rare species in Mojiang, Yunnan, China," *Chinese Journal of Plant Ecology* 42 (9), 938–945. DOI: CNKI:SUN:ZWSB.0.2018-09-005

11. Kou, J.Z. (2021). "The adjusted"list of national key protected wild plants"was officially announced," *People's Daily*. Beijing, 14. DOI: 10.28655/n.cnki.nrmrb.2021.009629
12. Wang, S.G., Pu, X.L., Ding, Y.L., Wan, X.C., Lin, S.Y. (2009). "Morphological differences of *Fargesia yunnanensis* fiber," *Journal of Zhejiang A & F University* 26(4), 528-532. DOI: 10.3969/j.issn.2095-0756.2009.04.013
13. Niu, S.J., Wang, N., Cui, B.X., Wang, C.G., Wu, H., Zhang, S.Y. (2023). "Effects of different ages and positions on fiber morphology and crystallinity of *Phyllostachys edulis*," *Journal of Zhejiang A & F University* 40(02), 446-452. DOI: 10.11833/j.issn.2095-0756.20220749
14. Li, W.C., Wang, S.D., Zhou, Y., Ding, Y.L. (2010). "A study fiber morphological structure of *Oxytenanthera braunii*," *Journal of Bamboo Research* 29(01), 40-44. DOI: 10.3969/j.issn.1000-6567.2010.01.009
15. Chen, L.J., Zhang, C.Y., Lai, Y.P., Zhang, Y.C., Gan, X.H. (2015). "Fiber morphology of six sympodial bamboos in Sichuan," *Journal of Northwest A & F University (Nat. Sci. Ed.)* 43(05), 79-86. DOI: 10.13207/j.cnki.jnwafu.2015.05.031
16. Meng, F.D. (2011). "Manufacturing technology and properties of scrimber of bamboo fibrillated-veneer lumber," Dissertation, Northeast Forestry University.
17. Delgado, P.S., Lana, S.L.B., Ayres, E., Patrício, P.O.S., Oréface, R.L. (2012). "The potential of bamboo in the design of polymer composites," *Materials Research* 15(4), 639-644. DOI: 10.1590/S1516-14392012005000073
18. Zhan, H., Xie, D.B., Li, M.B., Li, J., Yu, L.X., Wang, C.M., Wang, S.G. (2022). "Fiber properties and chemical compositions of sheaths from three selected sympodial bamboo species as raw materials for papermaking in Yunnan of China," *European Journal of Wood and Wood Products* 81, 815-818. DOI: 10.1007/s00107-022-01915-2
19. Xu, R., He, H.L., Guo, H.J., Zhu, F.W., Wang, S.G., Dai, C.F., Zheng, X.F., Xie, D.B., Li, H.M., Wang, C.M., Zhan, H. (2023). "Characteristics of silicon and phytolith distribution in bamboo (*Ferocalamus strictus*): variations between different organs and ages," *Review of Palaeobotany and Palynology* 311, 104817. <http://dx.doi.org/10.1016/j.revpalbo.2022.104817>. 10.1016/j.revpalbo.2022.104817
20. He, H.L., Zheng, X.F., Wang, Y.Q., Wang, W.Q., Li, M.B., Wang, S.G., Wang, J., Wang, C.M., Zhan, H. (2022). "Effects of climate change and environmental factors on bamboo (*ferrocalamus Strictus*), a PSESP unique to China," *Forests* 13(12), 2108. <https://doi.org/10.3390/f13122108>
21. Wang, Y.J., Qi, Q.W., Bao, Z.Y., Wu, L.L., Geng, Q.L., Wang, J. (2022). "A novel sampling design considering the local heterogeneity of soil for farm field-level mapping with multiple soil properties," *Precision Agriculture* 24(1), 1-22. DOI: 10.1007/s11119-022-09926-y
22. Zhang, W., Li, W.B., Yao, W.B. (2007). "A preliminary study on the separation mechanism and preparation method of natural bamboo fiber," *Journal of Beijing Forestry University* 29(04), 63-66. DOI: 10.13332/j.1000.1522.2007.04.015
23. China Forestry Industry Standard (CFIS). (1999). "Determination of Total Silica, Iron, Aluminium, Calcium, Magnesium, Potassium, Sodium, Phosphorus, Sulphur, Manganese, Copper and Zinc in

Forest Plant and Forest Floor. LY/T 1270-1999," *Standards Press of China*, Beijing.

24. Li, Q., Lin, J.G., Huang, Q.Y., Wu, Q.R. (2017). "Fiber Morphology Properties in Different Positions of the Culm of Three-year-old *Bambusa longispiculata* Gamble," *China Pulp & Paper* 36(06), 21-25. DOI: 10.11980/j.issn.0254-508X.2017.06.005
25. Zhan, H., Tang, G.J., Wang, C.M., Wang, S.G. (2015). "Chemical properties and fiber morphology of *Dendrocalamus hamiltonii* as potential pulp material," *European Journal of Wood and Wood Products* 74, 273-276. DOI: 10.1007/s00107-015-0993-y
26. Liese, W. (1985). "Anatomy and properties of bamboo," In: *Proceedings of the International Bamboo Workshop*, Hangzhou, China, 196-208.
27. Gao, G.A., Li, Z.Z. (2010). "Study on Morphological Characteristics of Sweet Bamboo Fiber from Vietnam," *Forest Products Chemistry and Industry* 30(01), 39-42. DOI: CNKI:SUN:LCHX.0.2010-01-010
28. Cao, C. (2022). "Study on chemical composition of culm and stem of 28 species of bamboo," Dissertation, Sichuan Agricultural University. DOI: 10.27345/d.cnki.gsnyu.2022.000457
29. Mayowa, A.A., Andrew, J.E., Bruce, S.B. (2016). "A preliminary investigation of nigerian *gmelina arborea* and *bambusa vulgaris* for pulp and paper production," *Maderas Ciencia Y Tecnología* 18(ahead), 0-0. DOI: 10.4067/S0718-221X2016005000007
30. Wang, C.M., Wang, J., Wang, W.J., Mu, Q.Y., Deng, Q.P. (2008). "The property and papermaking performance of the major bamboo species in Yunnan province," *China Pulp & Paper* (08), 10-12, 22. DOI: 10.3969/j.issn.0254-508X.2008.08.003
31. Jing, X., Fang, S.H., Su, W.H., Chu, H.Y., Zheng, Y.X., Luo, H.Y., Shen, J.X. (2022). "Evaluation of chemical characteristics of pulping of six symbiotic bamboo species in Meishan, Sichuan," *Chinese Journal of Ecology* 41(04), 648-653. DOI: 10.13292/j.1000-4890.202203.018
32. Yusuf, S., Syamani, F.A., Fatriasari, W., Subyakto. (2018). "Review on bamboo utilization as biocomposites, pulp and bioenergy," *IOP Conference Series-Earth and Environmental Science* (141), 1-13. DOI: 10.1088/1755-1315/141/1/012039
33. Wyszowski, Mirosław, Modrzewska, Beata, Kosiorek, Milena. (2016). "Levels of selected trace elements in scots pine (*pinus sylvestris* L.), silver birch (*betula pendula* L.), and norway maple (*acer platanoides* L.) in an urbanized environment," *Environ Monit Assess* 188, 598. DOI: 10.1007/s10661-016-5600-0
34. Zupancic, Nina. (2017). "Influence of climate factors on soil heavy metal content in Slovenia," *Journal of soil and sediments* (4), 1073-1083. <http://dx.doi.org/10.1007/s11368-016-1614-z>. DOI: 10.1007/s11368-016-1614-z
35. Ivani, M., Turk, M.F., Tkalec, Z., Fiket, E., Mei, A. (2021). "Distribution and origin of major, trace and rare earth elements in wild edible mushrooms: urban vs forest areas," *Journal of fungi (Basel, Switzerland)* 7(12), 1068-1068. DOI: 10.3390/jof7121068
36. Wu, M., Li, D., Li, H., Tang, D.Y., Zheng, Y.L. (2023). "Study on the content and influencing factors of trace elements in surface soil of puning city," *Leather Manufacture and Environmental Technology* 4(05), 183-185. DOI: 10.20025/j.cnki.CN10-1679.2023-05-63

37. Zhang, Z.C., Shi, Z., Yang, J., Hao, B., Hao, L., Diao, F., Wang, L., Bao, Z., Guo, W. (2021). "A new strategy for evaluating the improvement effectiveness of degraded soil based on the synergy and diversity of microbial ecological function-sciencedirect," *Ecological Indicators* 120(2), 106917. DOI: 10.1016/j.ecolind.2020.106917
38. Bai, S.B., Conant, R.T., Zhou, G.M., Wang, Y.X., Wang, N., Li, Y.H., Zhang, K.Q. (2016). "Effects of moso bamboo encroachment into native, broad-leaved forests on soil carbon and nitrogen pools," *Scientific Reports* 6. DOI: 10.1038/srep31480
39. Liu, G.L., Fan, S.H., Guan, F.Y., Du, M.Y., Huang, Y.N. (2010). "Distribution pattern of nutrient elements and its relationship with soil environment in different aged *phyllostachys edulis*," *Forest Research* 23(2), 252-258. DOI: 10.3724/SP.J.1238.2010.00474

Figures



Figure 1

Fibers of *Ferrocalamus strictus* culm obtained by segregation

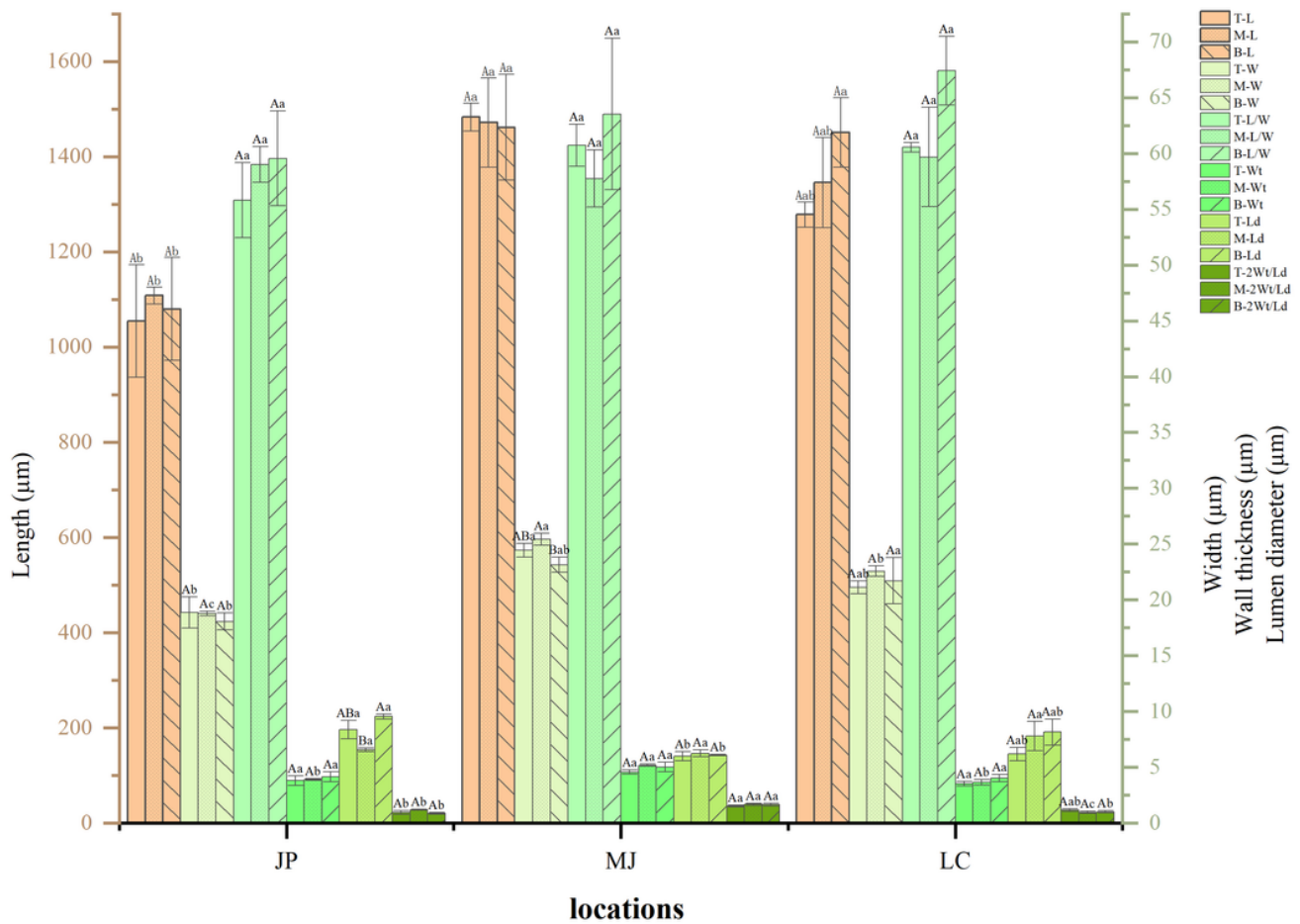


Figure 2

Fiber morphology of *Ferrocalamus strictus* in different culm portions

Note: "L" indicated fiber length, "W" indicated fiber width, "Wt" indicated fiber wall thickness, "Ld" indicated fiber lumen diameter, "T" indicated top portion of the culm, "M" indicated middle portion of culm, "B" indicated bottom portion of culm.

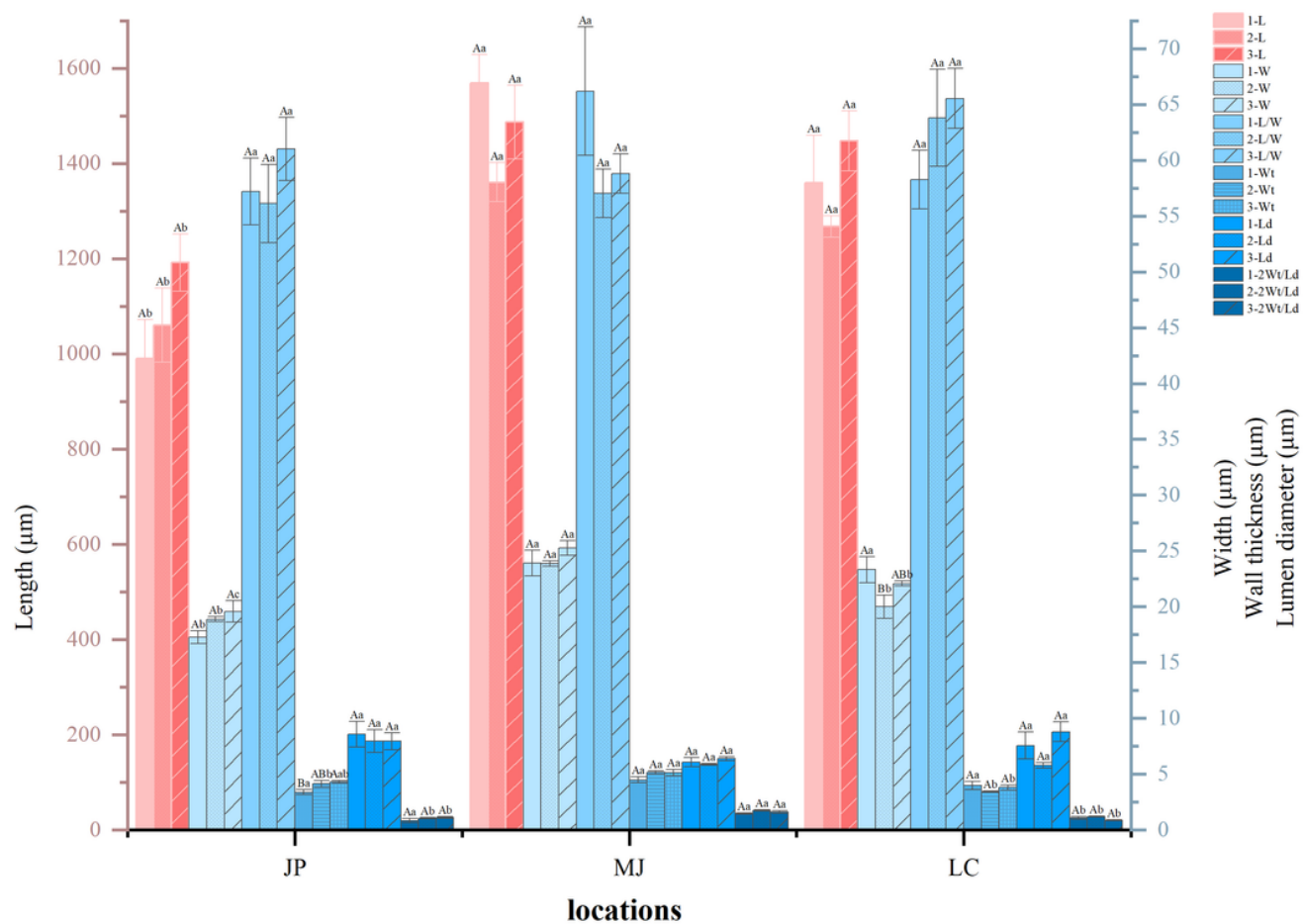
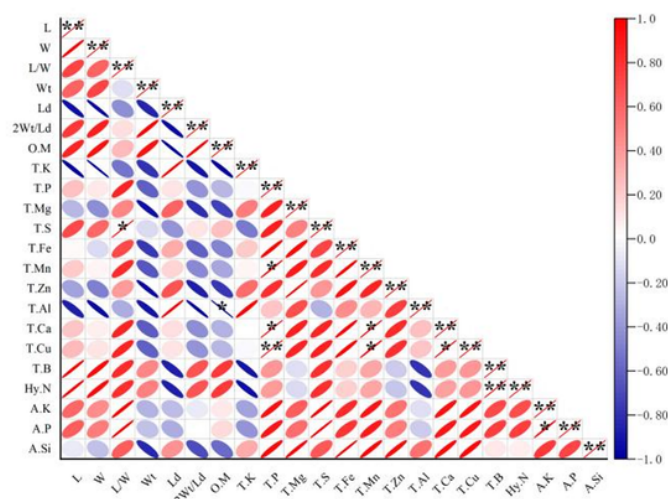
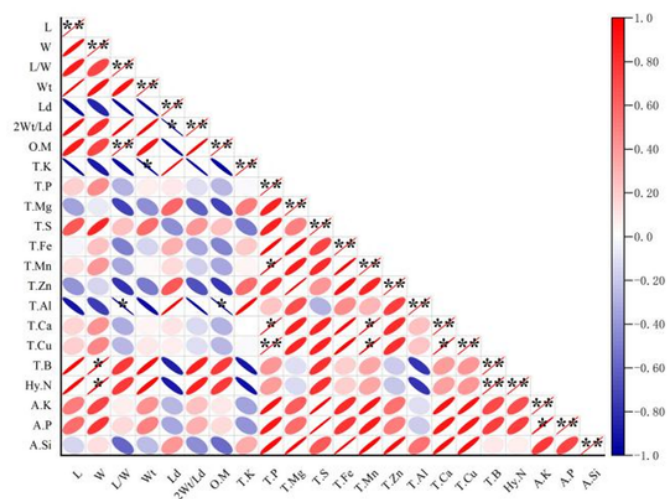


Figure 3

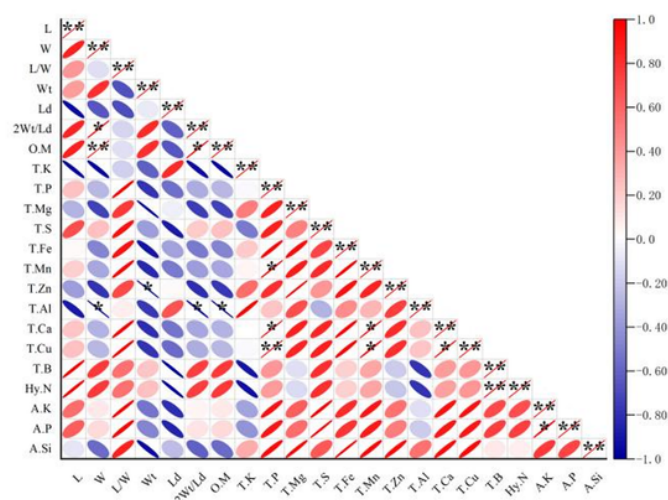
Fiber morphology of *Ferocalamus strictus* culm in different ages



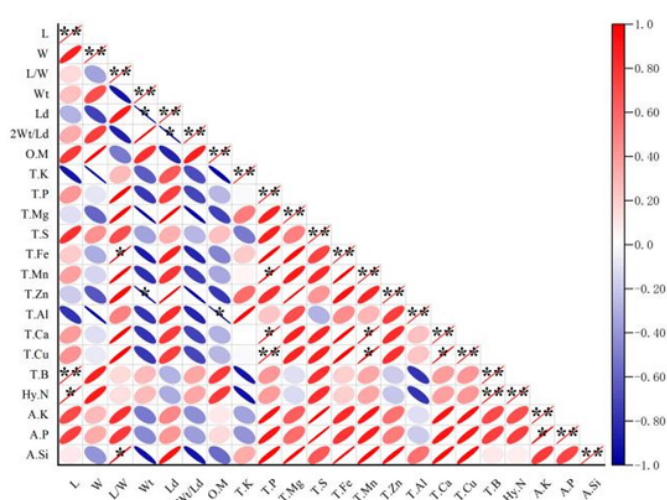
Correlation between fiber morphology (mean) and soil elements



Correlation between fiber morphology of 1-year culm and soil elements



Correlation between fiber morphology of 2-year culm and soil elements



Correlation between fiber morphology of 3-year culm and soil elements

Figure 4

Correlation analysis of fiber morphology and elements of iron bamboo (* $P \leq 0.05$ ** $P \leq 0.01$)