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

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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 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 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.

Keywords *Ferrocalamus strictus*, Fiber morphology, Soil elements

Introduction

Bamboo is considered to be an important type of forest resource with long fiber length, rapid growth and excellent timber properties [1]. China is rich in bamboo resources, with a total of 941 species in 43 genera, nearly 50% of which are distributed in Yunnan Province [2]. With the overextraction of timber resources, the conflict between supply and demand continues to aggravate, the expansion of bamboo plantations for pulp and paper-making [2], furniture decoration [4], artificial composite boards [5] and fiber textiles [6] provides an alternative solution.

Ferrocalamus strictus is a type species of *Ferrocalamus* in the subfamily Bambusoideae. It was discovered by

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Bojie Geng and Jiru Xue in 1982 and named for its hard culm [7, 8]. It is one medium-sized monopodial bamboo [9], with the internode length above 100 cm, which is a good material for making chopsticks and woolen needles [7, 8]. 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 [8], and listed as a China key national first-class protected wild plant in 2021 [10].

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. [10] and Niu et al. [12] 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. [13] 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. [14] 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. [15] 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. [16] analyzed the availability of bamboo fiber composites in product packaging. Zhan et al. [17] 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.

Materials and methods

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).

The samples were collected in the sunny weather in June, and the growth conditions of the samples were guaranteed to be consistent. Sampling was referred to the method from Xu et al. [2]. Three bamboo culms of *F. strictus* from three distribution areas in each of the three age groups (1, 2, and ≥ 3 years old) were cuted. 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.

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
The mean diameter of culms (mm)	20.60	19.32	17.94
The mean thickness of culms (mm)	3.70	3.51	3.35

Soil collection was referred to the method from Wang et al. [18].

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 h. The soil was cleared of debris and passed the screens for 400 mesh and 200 mesh sieves.

Methods

The fiber extraction of *F. strictus* culms, referring to the segregation method of Zhang et al. [19]. Firstly, the separation process was carried out: the bamboo was split into a matchstick size, 1–2 roots were placed in a test tube, the separation solution (hydrogen peroxide: glacial acetic acid=1: 1) was added, and then heated in a water bath at 95 °C until the sample faded and whitened. Secondly, dyeing process: wash the separated sample to neutral, add the safranin dye for at least 24 h, and then wash the sample to neutral. Finally, add an appropriate amount of pure water to preserve.

Got a cross section of *F. strictus* by field investigations (Fig. 1), and the fibers of *F. strictus* obtained by separation experiment (Fig. 2), A is the transverse section of the *F. strictus*, B is the longitudinal section, and C is the free fiber after segregation treatment. 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 ImageJ 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 [20]. SPSS26.0 and Origin2021 software were used for data analysis.



Fig. 1 The cross section of 2-year culm in *Ferrocalamus strictus*

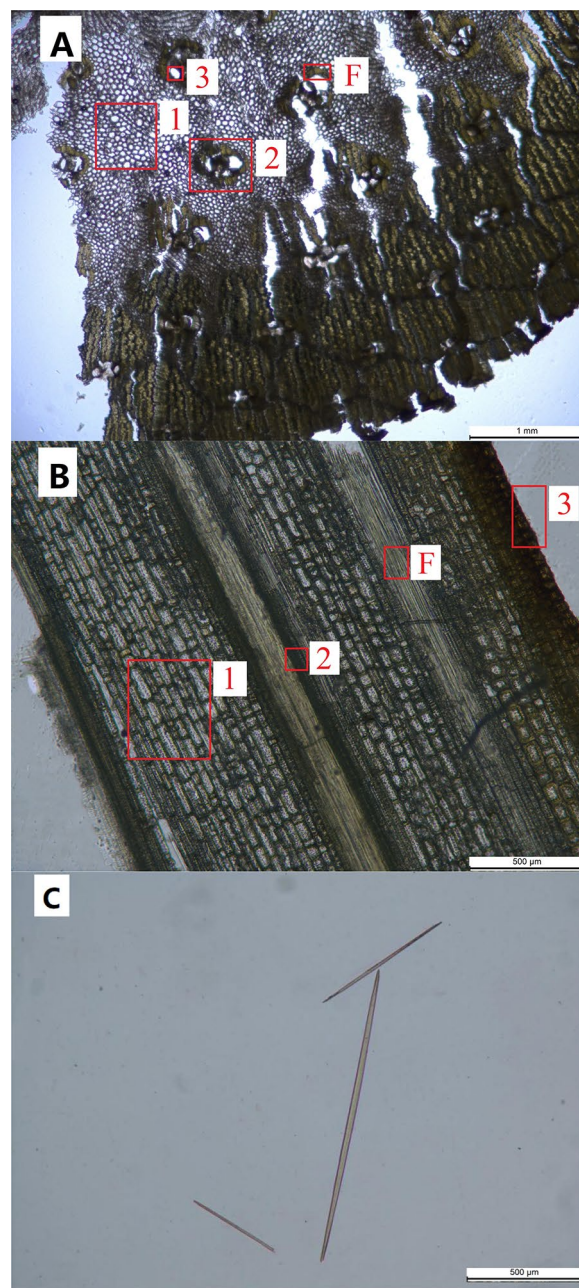


Fig. 2 The fibers of *Ferrocalamus strictus* culm. These pictures are from the middle portion of 2-year culm in *Ferrocalamus strictus* in Mojiang County. The "A-1, A-2, A-3, F" indicated the parenchyma cells, vascular bundle, metaxylem, fibers. The "B-1, B-2, B-3, F" indicated the parenchyma cells, cells between fiber bundles and parenchyma cells, outer epidermis, fibers

Results

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 . In Fig. 3, the difference of fibers between portions (in the same location) can be observed, and the difference of fibers between locations (in the same portions) can also be

observed. In Fig. 4, the difference of fibers between ages (in the same location) can be observed, and the difference of fibers between locations (in the same ages) can also be observed. The Table 2 shows the average value of fiber in locations, ages and portions.

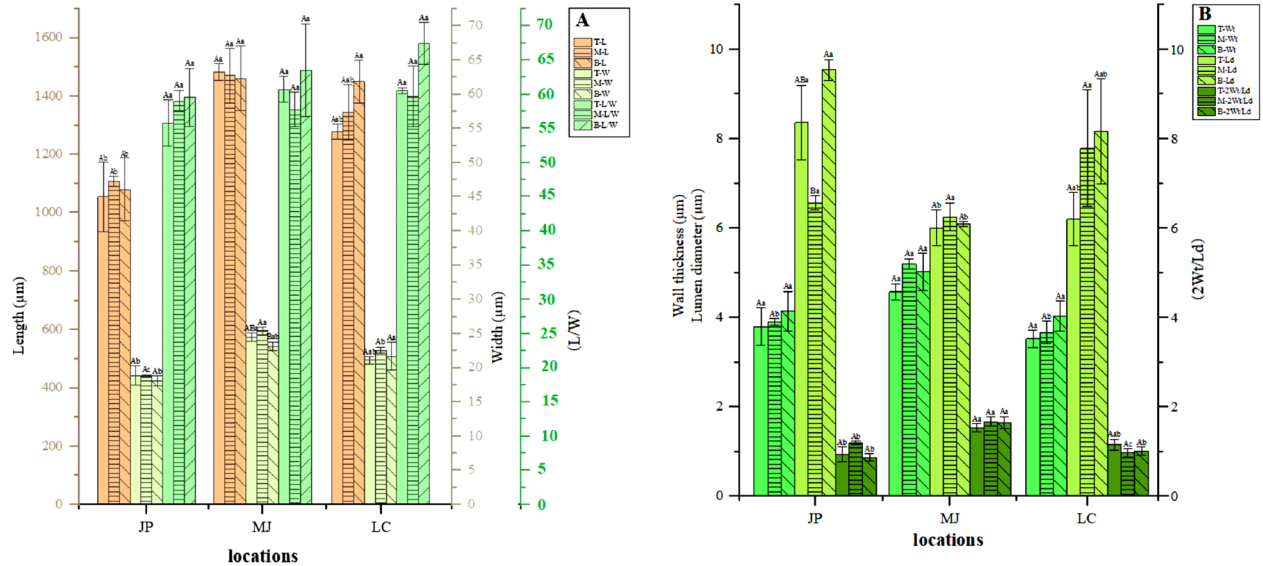


Fig. 3 The fiber morphology of *Ferrocalamus strictus* in different culm portions. The “L, W, Wt, Ld, L/W, 2Wt/Ld” indicated fiber length, width, wall thickness, lumen diameter, slenderness ratio, runkel ratio; the “T, M, B” indicated top portion of the culm, middle portion of culm, bottom portion of culm. Uppercase letters indicate differences between the same culm portions in different locations at 0.05 probabilities, lowercase letters indicate differences between different culm portions in same location at 0.05 probabilities

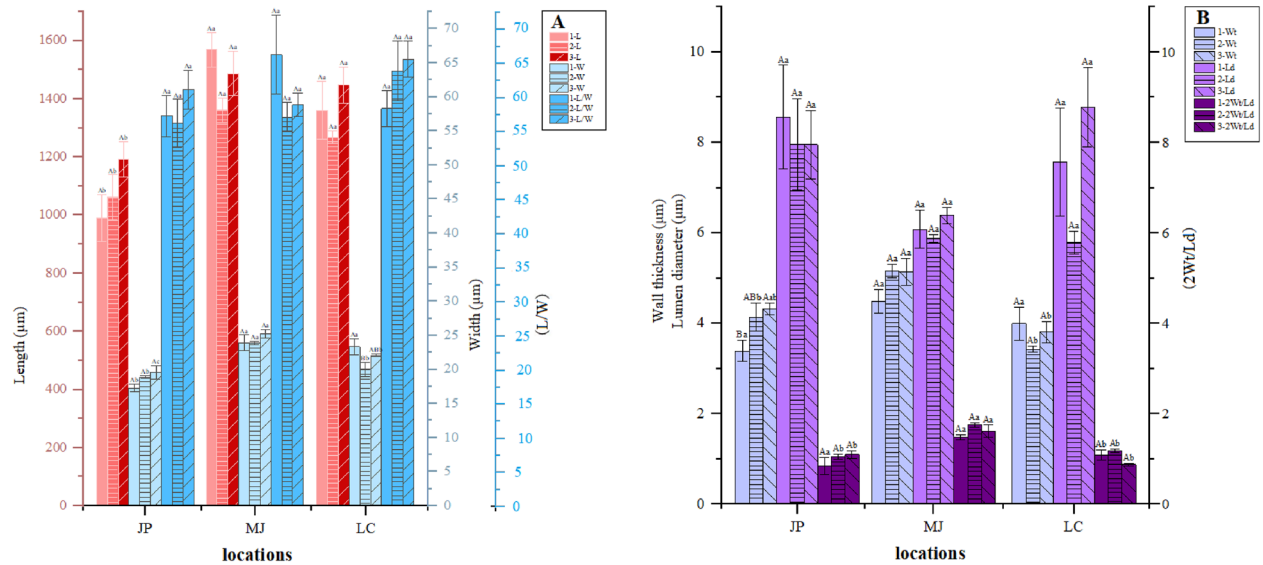


Fig. 4 The fiber morphology of *Ferrocalamus strictus* culm in different ages. The “L, W, Wt, Ld, L/W, 2Wt/Ld” indicated fiber length, width, wall thickness, lumen diameter, slenderness ratio, runkel ratio; the “1-, 2-, 3-” indicated 1-year culms, 2-year culms, 3-year culms. Uppercase letters indicate differences between the same culm ages in different locations at 0.05 probabilities, lowercase letters indicate differences between different culm ages in same location at 0.05 probabilities

Table 2 The mean value of fiber morphology of 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

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

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. 3, Table 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 MJ, LC and JP. The mean of fiber slenderness ratio was the greatest in LC (62.54) 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 significantly larger than that of the MJ. The runkel ratio of the MJ was significantly larger than that of the JP and LC.

In JP, the fiber length, width, slenderness ratio wall thickness and runkel ratio 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 (Fig. 4). However, insignificant difference in fiber length was observed among different portions of the culm. The lumen diameter of the bottom portion of the culm was significantly greater than the middle portions (Fig. 3).

In MJ, the greatest fiber length and slenderness ratio was found in 1-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 1- and 3-year culms (Fig. 4). The middle portions had significantly larger the width than the top and bottom portions. No significant difference in length, slenderness ratio, wall thickness and

runkel ratio were observed among different portions of the culm (Fig. 3).

In LC, the greatest fiber length, slenderness ratio and lumen diameter was found in 3-year culms. The width and wall thickness of 1-year culms was significantly greater than that of 2- and 3-year culms, whereas the smallest slenderness ratio was observed in 1-year culms. The fiber slenderness ratio presented a increasing trend with increasing culm ages (Fig. 4). The bottom portion had greater fiber length, slenderness ratio, wall thickness and lumen diameter than the top and middle portions. The fiber wall thickness and lumen diameter presented a increasing trend with the culm portions from top to bottom. No significant differences in the slenderness ratio was observed among different culm portions (Fig. 3).

Morphological characteristics of culm fibers in different ages

The fiber average wall thickness in *F. strictus* culm increased with the culm ages and reached the maximum values in 3-year culm. The fiber average length, average width, average slenderness ratio, average wall thickness and average lumen diameter of 3-year culms was the largest in different ages, while the fiber runkel ratio was the largest of 2-year culms. The fiber average length, average width, average slenderness ratio and average lumen diameter were the smallest in 2-year culms in different ages. No significant differences in the average relative fiber index measured were observed among different culm ages (Table 2).

For the 1-year culms, no significant differences in the length, width, slenderness ratio, lumen diameter and runkel ratio were observed among different locations: the fiber length, width and wall thickness of MJ and LC was

larger than that of JP, the fiber lumen diameter of JP and LC was larger than that of MJ (Fig. 4).

For the 2-year culms, the fiber width, wall thickness and runkel ratio of the MJ had larger than that of the JP and LC. The fiber slenderness ratio of the LC were larger than that of the MJ and JP. The lumen diameter of the JP was the largest (Fig. 4).

In the 3-year culms, the fiber length of JP had significantly smaller than the MJ and LC. The LC had significantly smaller fiber wall thickness than the MJ and JP. The JP and LC had significantly smaller runkel ratio than the MJ. No significant differences in the fiber slenderness ratio and lumen diameter were observed among different locations: the fiber width of culm had difference in locations and the fiber width of the MJ was largest (Fig. 4).

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 average length, average wall thickness and average lumen diameter were 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. 3). No significant differences in the length, width, slenderness ratio, wall thickness, lumen diameter and runkel ratio were observed among different culm portions (Table 2).

For the top portion of the culms, the fiber length and width of MJ had larger than that of JP. No significant differences in the slenderness ratio, wall thickness and runkel ratio were observed among different locations (Fig. 3).

For the middle portion of the culms, the fiber length of MJ had significantly larger than that of JP, the wall thickness of MJ had significantly larger than that of JP and LC. No significant differences in the slenderness ratio was observed among different locations: the fiber width was difference in the order of MJ > LC > JP, the runkel ratio was difference in the order of MJ > JP > LC (Fig. 3).

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 (Fig. 3).

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 1.6 mm, and long fiber is above 1.6 mm [21]. The proportion of long and medium fibers were larger than that of short fibers 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).

Soil elements in different locations

The elements content varied in locations, the content of total phosphorus, total magnesium, total sulfur, total iron, total manganese, total zinc, total calcium, total copper, available potassium, available phosphorus and available silicon in LC was the larger than the JP and MJ, which were the largest. The content of organic matter, total boron and alkali-hydrolyzed nitrogen in MJ was the larger than the JP and LC, which were the largest. The content of total aluminum and total potassium in JP was the larger than the MJ and LC, which were the largest (Table 4).

The content of organic matter, total boron and alkali-hydrolyzed nitrogen in the soil from MJ was largest than those in JP and LC. The organic matter content in the soil

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 ≤ 0.9	34.6	6.4	10.7	20.0	20.4	11.2	20.4	14.6	19.6	17.5
0.9 ≤ L ≤ 1.6	55.4	57	66.3	55.9	62.1	60.7	59.3	61.3	57.4	59.5
1.6 ≤ L	10	36.6	23	24.1	17.5	28.1	20.3	24.1	23.0	23.0

Table 4 Differences in soil elements in locations

Element	Location		
	JP	MJ	LC
Organic matter (O. M g/kg)	59.51 ± 2.25B	109.57 ± 15.54A	70.96 ± 3.53AB
Total potassium (T.K g/kg)	35.64 ± 0.89A	7.96 ± 0.59C	22.37 ± 0.13B
Total phosphorus (T.P g/kg)	0.53 ± 0.02B	0.56 ± 0.01B	1.52 ± 0.17A
Total magnesium (T.Mg g/kg)	3.30 ± 0.11B	1.16 ± 0.08C	5.57 ± 0.33A
Total sulfur (T.S g/kg)	0.40 ± 0.01B	0.49 ± 0.02AB	0.57 ± 0.06A
Total iron (T.Fe g/kg)	27.08 ± 0.86B	23.00 ± 0.88C	42.84 ± 0.37A
Total manganese (T.Mn mg/kg)	185.67 ± 4.98B	159.75 ± 5.04B	1022.00 ± 78.00A
Total zinc (T.Zn mg/kg)	83.33 ± 1.76B	37.00 ± 11.03C	120.00 ± 1.00A
Total aluminum (T.Al g/kg)	95.10 ± 1.67A	41.18 ± 2.69C	80.96 ± 0.75B
Total calcium (T.Ca g/kg)	0.34 ± 0.03B	0.38 ± 0.04B	6.71 ± 2.49A
Total copper (T.Cu mg/kg)	7.10 ± 0.85B	8.68 ± 1.37B	45.80 ± 1.30A
Total boron (T.B mg/kg)	6.10 ± 0.90B	26.53 ± 1.66A	23.60 ± 3.10A
Alkali-hydrolyzed nitrogen (Hy.N mg/kg)	200.67 ± 9.68B	271.00 ± 16.91A	260.00 ± 2.00A
Available potassium (A.K mg/kg)	112.00 ± 15.53B	143.75 ± 13.12AB	195.50 ± 11.50A
Available phosphorus (A.P mg/kg)	2.26 ± 0.40C	6.87 ± 0.94B	12.70 ± 2.23A
Available silicon (A.Si mg/kg)	65.00 ± 3.06B	24.50 ± 2.99B	156.50 ± 52.50A

from MJ (109.57 g/kg) was significantly higher than that from JP (59.51 g/kg), the total boron content in the soil of MJ (26.53 mg/kg) and LC (23.6 mg/kg) were significantly higher than that in JP (6.10 mg/kg), and the alkali-hydrolyzed nitrogen content in MJ (271.00 mg/kg) and LC (260.00 mg/kg) was significantly greater than that in JP (200.67 mg/kg) (Table 4).

The contents of total phosphorus, total sulfur, total calcium, total copper and available phosphorus in the soil from LC was largest. The total phosphorus content in the soil from JP (0.53 g/kg) and MJ (0.56 g/kg) was significantly smaller than that in LC (1.52 g/kg). The soil from LC had higher total sulfur content (0.57 g/kg) than JP (0.40 g/kg). 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 g/kg), LC (22.37 g/kg), MJ (7.96 g/kg). The total aluminum content showed the regularity in the soil, followed by JP (95.10 g/kg), LC (80.96 g/kg), MJ (41.18 g/kg). The total magnesium, total iron, total zinc content showed the regularity in the soil, followed by LC, JP, MJ. The total manganese content showed the regularity in the soil, followed by LC, MJ, JP (Table 4).

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. 5).

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 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 ($P < 0.05$).

Discussion

Fiber morphology

Analysis of the fiber morphology of *F. strictus* culms in different locations showed that the fiber morphology index of MJ culms changed less than that of JP and LC. The maximum fiber index including fiber length, width, slenderness ratio, wall thickness and runkel ratio was

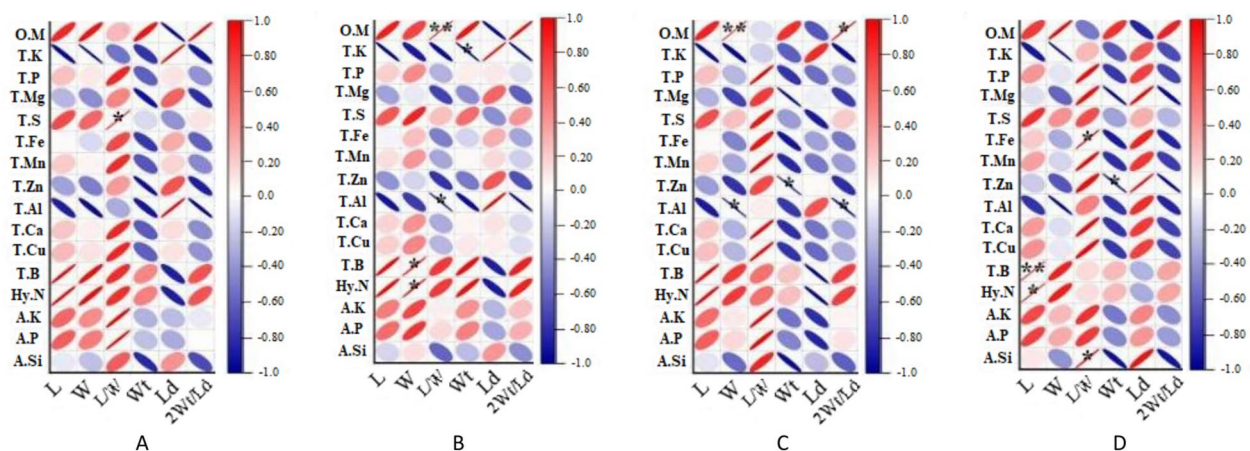


Fig. 5 Correlation analysis of fiber morphology and elements of iron bamboo (* $P \leq 0.05$; ** $P \leq 0.01$). The “A”: Correlation between fiber morphology (mean) and soil elements; the “B”: Correlation between fiber morphology of 1-year culm and soil elements; the “C”: Correlation between fiber morphology of 2-year culm and soil elements; the “D”: Correlation between fiber morphology of 3-year culm and soil elements. The higher correlation, the darker the circular color and the circular narrowing, the lower correlation, the lighter the circular color and the circular widening

obtained in the 1-year culms in MJ. This was inconsistent with the conclusions of Zhan et al. [22], 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 [23].

Generally, the slenderness ratio for good pulp raw materials needs to be larger than 30 [24]. The mean slenderness ratio of *F. strictus* culms in different locations was above 30. The average fiber length of *F. strictus* culm was in the range of 1.29–1.31 mm, the mean proportion of long and medium fibers were greater than that of short fibers in *F. strictus* culm [25, 26]. It is highly likely to become a papermaking raw material. 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 [27, 28], the fiber slenderness ratio of *F. strictus* culm was close to that of *Melocalamus compactiflorus*, *Bambusa blumeana*, *Schizostachyum funghomii* and *Bambusa vulgaris* [28], and the fiber length, width, wall thickness and runkel ratio were smaller, but the lumen diameter was larger.

Soil elements 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 [30], climate [31] and even human production activities [32] 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, boron and hydrolytic nitrogen in soil was the highest in MJ, which may support the conclusion of fiber morphology of *F. strictus* culm in MJ changed less than that of JP and LC. The content of soil elements in MJ can be used as a reference for bamboo forest cultivation.

Correlation between the fiber morphology and soil elements

In this study, the contents of organic matter, total boron 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 average slenderness ratio was significant positively correlated with the total sulfur content, no significant correlation in the others fibers morphology and the soil elements content. Wu et al. [33] and Zhang et al. [34] believed that soil elements promote or inhibit each other, and the positive correlation between the two indicates that elements may have similar input sources. In this experiment, organic matter content was significantly positively correlated with fiber width and diameter-cavity ratio. Therefore, organic matter and fiber morphology may have the same input source (the slenderness ratio of 1-years culms was positively correlated with the content of the organic matter, the width and runkel ratio of 2-years culms were positively correlated with the content of the organic matter), and fiber morphology is very likely to absorb organic matter from soil. However, aluminum content was negatively correlated with the fiber width, slenderness ratio and runkel ratio (the slenderness ratio of 1-years culms

was significantly negatively correlated with the aluminum content, the width and runkel ratio of 2-years culms were significantly negatively correlated with the aluminum content), so aluminum content and fiber morphology have different input sources. The cultivation of bamboo forest can consider adding elements that are positively correlated with fiber morphology to the soil to reduce the input of elements that are negatively correlated with fiber morphology.

Chen et al. [36] showed that there was no limiting effect between the two factors whose correlation was not obvious. 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, the mean of fiber length and was significantly positively correlated with the contents of total boron and alkali-hydrolyzed nitrogen. The study of Bai et al. [36] showed that the growth of bamboo forest needed a lot of nitrogen. In this experiment, the fiber length increased with the increase of age, which may increase the demand for nitrogen. The fiber width showed a widening trend in the 1-year-old stalk, and the fiber width was significantly positively correlated with the content of boron and hydrolyzed nitrogen. The content of boron and hydrolyzed nitrogen may be the limiting factor affecting the widening of fiber width [37]. Zhang et al. [38] believed that the factors without significant correlation were not the limiting factors affecting wheat yield. In this experiment, due to the significant negative correlation between fiber width and aluminum content of 2-year-old bamboo culm, aluminum content may be the limiting factor for the increase in fiber width. In the three-year period, the expansion trend of fiber width is not obvious. The correlation between fiber width and elements in different age classes is different, which may be due to the different limiting factors of fiber width at different growth stages, which is consistent with the conclusion of Liu et al. [38], that is the content of nitrogen, phosphorus, calcium, magnesium and other elements in bamboo culm changes with the increase in ages.

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), wall thickness (4.21 μm), lumen diameter (7.22 μm), and runkel ratio (1.22), 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 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.

Abbreviations

<i>F. strictus</i>	<i>Ferocalamus strictus</i>
JP	Huotandong Village in Jinping County
MJ	Lazhu Village in Mojiang County
LC	Taihong Village in Lvchun County

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Author contributions

Xiaofeng Zheng completed the writing of this work; Rui Xu completed the Ideation and revision of this work; Xiaofeng Zheng, Ziten Zhou and Jiamin Wang contributed equally to this work of the data processing; Honglan He, Yingqiong Wang and Xiaofeng Zheng took the samples; Hui Zhan and Changming Wang contributed equally to this work of revise; Jiayi Deng completed the A and B of the Fig. 2, that is the transverse section and longitudinal section of the *Ferocalamus strictus*. All author reviewed the manuscript.

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Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

None.

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References

- Ogunwusi AA, Ibrahim HD (2022) Advances the in utilization of bamboo for paper production and the implication for countries with bamboo resource. *J Resour Dev Manag* 83:18–26. <https://doi.org/10.7176/JRDM/83-03>
- Xu R, He HL, Guo HJ, Zhu FW, Wang SG, Dai CF, Zheng XF, Xie DB, Li HM, Wang CM, Zhan H (2023) Characteristics of silicon and phytolith distribution in bamboo (*Ferocalamus strictus*): variations between different organs and ages. *Rev Palaeobot Palynol* 311:104817. <https://doi.org/10.1016/j.revpalbo.2022.104817>
- Cai SX, Xia Y, Xu BJ, Guo YL (2020) Research on mechanical properties and design improvement of small diameter grade round bamboo furniture materials. *China For Prod Ind* 57(09):32–36. <https://doi.org/10.19531/j.issn1001-5299.202009008>
- Raydan ND, Leroyer L, Robles E (2021) Recent advances on the development of protein-based adhesives for wood composite materials-a review. *Molecules* 26(24):7617. <https://doi.org/10.3390/molecules26247617>
- Fu JJ, Li XQ, Silva C (2012) Bio-processing of bamboo fibres for textile applications: a mini review. *Biocatal Biotransform* 30(1):141–153. <https://doi.org/10.3109/10242422.2012.650450>
- Lian CP, Wang XH, Chen H, Fei BH, Pang XR, Lian JP, Wu ZH (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>
- Geng BJ, Xue JR (1982) *Ferocalamus strictus* genus - a new genus of bamboo in China. *J Bamboo Res* 1(2), 1–5. <https://kns.cnki.net/kcms/detail/detail.aspx?dbname=CJFD1982&filename=ZZYJ198202000&dbcode=CJFD>
- Li EL, Zhou J, Du F, Hou ZQ, Bureau MF (2015) Discovery of wild *Ferocalamus strictus* community in Mojiang County. *For Invent Plan* 40(04):55–56. <https://doi.org/10.3969/j.issn.1671-3168.2015.04.011>
- Yu DX, Du F, Shi M, Yang C, Dai J (2018) Community characteristics and population structure of *Ferocalamus strictus*, a rare species in Mojiang, Yunnan, China. *Chin J Plant Ecol* 42(9):938–945
- Kou JZ (2021) The adjusted“ list of national key protected wild plants” was officially announced. *People's Daily Beijing* 14:1. <https://doi.org/10.28655/n.cnki.nmr.2021.009629>
- Wang SG, Pu XL, Ding YL, Wan XC, Lin SY (2009) Morphological differences of *Fargesia yunnanensis* fiber. *J Zhejiang A & F Univ* 26(4):528–532. <https://doi.org/10.3969/j.issn.2095-0756.2009.04.013>
- Niu SJ, Wang N, Cui BX, Wang CG, Wu H, Zhang SY (2023) Effects of different ages and positions on fiber morphology and crystallinity of *Phyllostachys edulis*. *J Zhejiang A & F Univ* 40(02):446–452. <https://doi.org/10.11833/j.issn.2095-0756.20220749>
- Li WC, Wang SD, Zhou Y, Ding YL (2010) A study on fiber morphological structure of *Oxytena thera braunii*. *J Bamboo Res* 29(01), 40–44. https://www.zhangqiaokeyan.com/academic-journal-cn_journal-bamboo-research_thesis/0201260634519.html
- Chen LJ, Zhang CY, Lai YP, Zhang YC, Gan XH (2015) Fiber morphology of six sympodial bamboos in Sichuan. *J Northwest A F Univ* 43(05):79–86. <https://doi.org/10.13207/j.cnki.jnwafu.2015.05.031>
- Meng FD (2011) Manufacturing technology and properties of scrimber of bamboo fibrillated-veneer lumber. Dissertation, Northeast Forestry University, pp.1–11
- Delgado PS, Lana SLB, Ayres E, Patrício POS, Oréfice RL (2012) The potential of bamboo in the design of polymer composites. *Mater Res* 15(4):639–644. <https://doi.org/10.1590/S1516-14392012005000073>
- Zhan H, Xie DB, Li MB, Li J, Yu LX, Wang CM, Wang SG (2022) Fiber properties and chemical compositions of sheaths from three selected sympodial bamboo species as raw materials for papermaking in Yunnan of China. *Eur J Wood Wood Prod* 81:815–818. <https://doi.org/10.1007/s00107-022-01915-2>
- Wang YJ, Qi QW, Bao ZY, Wu LL, Geng QL, Wang J (2022) A novel sampling design considering the local heterogeneity of soil for farm field-level mapping with multiple soil properties. *Precision Agric* 24(1):1–22. <https://doi.org/10.1007/s11119-022-09926-y>
- Zhang W, Li WB, Yao WB (2007) A preliminary study on the separation mechanism and preparation method of natural bamboo fiber. *J Beijing For Univ* 29(04):63–66. <https://doi.org/10.13332/j.1000-1522.2007.04.015>
- LY/T 1270-1999 Determination of total Silica, iron, aluminium, calcium, magnesium, potassium, sodium, phosphorus, sulphur, manganese, copper and zinc in forest plant and forest floor. China Forestry Industry Standard (CFIS) (1999), Standards Press of China, Beijing
- Li Q, Lin JG, Huang QY, Wu QR (2017) Fiber morphology properties in different positions of the culm of three-year-old *Bambusa longispiculata* Gamble. *China Pulp Pater* 36(06):21–25. <https://doi.org/10.11980/j.issn.0254-508X.2017.06.005>
- Zhan H, Tang GJ, Wang CM, Wang SG (2016) Chemical properties and fiber morphology *Dendrocalamus hamiltonii* as potential pulp material. *Eur J Wood Wood Prod* 74:273–276. <https://doi.org/10.1007/s00107-015-0993-y>
- Liese W (1985) Anatomy and properties of bamboo. In: Proceedings of the International Bamboo Workshop, Hangzhou, China, pp.196–208
- Gao GA, Li ZZ (2010) Study on morphological characteristics of sweet bamboo fiber from Vietnam. *For Prod Chem Ind* 30(01):39–42
- Jing X, Fang SH, Su WH, Chu HY, Zheng YX, Luo HY, Shen JX (2022) Evaluation of chemical characteristics of pulping of six symbiotic bamboo species in Meishan, Sichuan. *Chin J Ecol* 41(04):648–653. <https://doi.org/10.13292/j.1000-4890.202203.018>
- Yusuf S, Syamani FA, Fatriasari W, Subyakto (2018) Review on bamboo utilization as biocomposites, pulp and bioenergy. *IOP Conf Ser-Earth Environ Sci* 141:1–13. <https://doi.org/10.1088/1755-1315/141/1/012039>
- Cao C (2022) Study on chemical composition of culm and stem of 28 species of bamboo. Dissertation, Sichuan Agricultural University, pp.5–26. <https://doi.org/10.27345/d.cnki.gsnyu.2022.000457>
- Mayowa AA, Andrew JE, Bruce SB (2016) A preliminary investigation of nigerian *Gmelina arborea* and *Bambusa vulgaris* for pulp and paper production. *Maderas Ciencia Y Tecnología* 18:65–78. <https://doi.org/10.4067/S0718-221X2016005000007>
- Wang CM, Wang J, Wang WJ, Mu QY, Deng QP (2008) The property and papermaking performance of the major bamboo species in Yunnan province. *China Pulp Paper* 08:10–12. <https://doi.org/10.3969/j.issn.0254-508X.2008.08.003>
- Milena K, Beata M, Mirosław W (2016) Levels of selected trace elements in Scots pine (*Pinus sylvestris*), silver birch (*Betula pendula*), and Norway maple (*Acer platanoides*) in an urbanized environment. *Environ Monit Assess* 188:598. <https://doi.org/10.1007/s10661-016-5600-0>
- Zupancic N (2017) Influence of climate factors on soil heavy metal content in Slovenia. *J Soil Sediments* 4:1073–1083. <https://doi.org/10.1007/s11368-016-1614-z>
- Ivani M, Turk MF, 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. *J Fungi (Basel, Switzerland)* 7(12):1068–1068. <https://doi.org/10.3390/jof7121068>
- Wu M, Li D, Li H, Tang DY, Zheng YL (2023) Study on the content and influencing factors of trace elements in surface soil of puning city. *Leather Manuf Environ Technol* 4(05):183–185. <https://doi.org/10.20025/j.cnki.CN10-1679.2023-05-63>
- Zhang ZC, 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-science. *Ecol Ind* 120(2):106917. <https://doi.org/10.1016/j.ecolind.2020.106917>
- Chen H, Cao CF, Kong LC, Zhang CL, Li W, Qiao YQ, Du SZ, Zhao Z (2014) Study on wheat yield stability in huabei lime concretion black soil area based on long-term fertilization experiment. *Scientia Agricultura Sinica* 47(13):2580–2590. <https://doi.org/10.3864/j.issn.0578-1752.2014.13.010>
- Bai SB, Conant RT, Zhou GM, Wang YX, Wang N, Li YH, Zhang KQ (2016) Effects of moso bamboo encroachment into native, broad-leaved forests on soil carbon and nitrogen pools. *Sci Rep* 6:1–8. <https://doi.org/10.1038/srep31480>
- Zhang CL, Chen LT, Cao CF, Kong LC, Ji YM (2005) Study on the contribution of Shajiang black soil fertilizer and the appropriate technical measures of applying fertilizer. *Chin Agric Sci Bull* 21(11):244–246
- Liu GL, Fan SH, Guan FY, Du MY, Huang YN (2010) Distribution pattern of nutrient elements and its relationship with soil environment in different aged *Phyllostachys edulis*. *For Res* 23(2):252–258. <https://doi.org/10.3724/SP.J.1238.2010.00474>

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