Scientific Reports
https://doi.org/10.1038/s41598-025-34834-2

Article in Press

Geographical variation in the quality of *Chimonobambusa rigidula* bamboo shoots and its relationship with site environment

Received: 29 July 2025

Accepted: 31 December 2025

Published online: 08 January 2026

Cite this article as: Fu Q., Chen Y., Liu F. *et al.* Geographical variation in the quality of *Chimonobambusa rigidula* bamboo shoots and its relationship with site environment. *Sci Rep* (2026). https://doi.org/10.1038/s41598-025-34834-2

Qinchao Fu, Yuelin Chen, Fang Liu, Jixian Liu, Qinlan Guan & Bo Zhao

We are providing an unedited version of this manuscript to give early access to its findings. Before final publication, the manuscript will undergo further editing. Please note there may be errors present which affect the content, and all legal disclaimers apply.

If this paper is publishing under a Transparent Peer Review model then Peer Review reports will publish with the final article.

ARTICLE IN PRESS

© The Author(s) 2026. **Open Access** This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by-nc-nd/4.0/.

ARTICLE IN PRESS

Geographical Variation in the Quality of *Chimonobambusa rigidula* Bamboo Shoots and Its Relationship with Site Environment

Qinchao Fu[1], Yuelin Chen[2], Fang Liu[3], Jixian Liu[3], Qinlan Guan[3], Bo Zhao[4*]

1. Natural Science Museum of Leshan Normal University, Key Laboratory of Sichuan Province for Bamboo Pests Control and Resource Development, Leshan Normal University, Leshan 614000, China;

2. Leshan Academy of Forestry, Leshan 614000, China;

3. School of Life Science, Leshan Normal University, Leshan, 614000, China;

4.Engineering Research Center of Biomass Materials, Ministry of E ducation, College of Life Sciences and Agri-forestry, Southwest University of Science and Technology, Mianyang, 621010, China;

Email:

Qinchao Fu: fuqinchao@lsnu.edu.cn

Yuelin Chen: chenyuelin0833@163.com

Fang Liu: liufang9028@ lsnu.edu.cn

Jixian Liu: liu10015082@163.com

Qinlan Guan: 15281930268@163.com

Bo Zhao: bozhao@swust.edu.cn

ARTICLE IN PRESS

ARTICLE IN PRESS

* Correspondence with: Prof. Bo Zhao (E-mail: bozhao@swust.edu.cn), Engineering Research Center of Biomass Materials, Ministry of Edu cation, College of Life Sciences and Agri- forestry, Southwest University of Science and Technology, Mianyang, 59# Qinglong road, Mianyang, 621010, People's Republic of China

Abstract: *Chimonobambusa rigidula* bamboo shoots are an important health-promoting vegetable. This study aims to identify the primary environmental factors influencing the quality of bamboo shoots across various regions, thereby providing a scientific foundation and theoretical support for managing this plant and enhancing shoot quality. The results indicate that the minimum and maximum temperatures in September, along with total soil phosphorus content, soil pH, and total soil nitrogen content, are the five critical factors affecting bamboo shoot quality and should be prioritized during the site selection process for bamboo shoot cultivation. The cumulative variation explanation rate for bamboo quality concerning environmental factors was found to be 90.22%. The appearance, morphology, and taste of bamboo shoots from Muchuan and Pingshan are superior to those from Mabian. Notably, bamboo shoots from Mabian exhibit the highest content of essential amino acids, while bamboo shoots from

ARTICLE IN PRESS

Muchuan contain the highest levels of mineral elements. This study provides new insights into the interactions between plant environments and *Chimonobambusa rigidula* bamboo shoot nutrition, offering actionable strategies for region-specific cultivation that align with consumer demand for healthier bamboo-based products.

Key words: Bamboo shoot quality; geographical variation; site environment; correlation analysis; redundancy analysis

ARTICLE IN PRESS

1 Introduction

The quality of bamboo shoots is a critical factor that reflects their economic value and market potential, serving as a key indicator for evaluating high-quality bamboo shoots [1]. This quality encompasses both external morphology and nutritional components. External morphology includes indicators such as shoot length, weight, and basal diameter, representing the most intuitive aspects of bamboo shoot quality. Nutritional components refer to the essential nutrients in bamboo shoots, including basic nutritional elements and amino acid content. Bamboo shoots are abundant in dietary fiber, protein, amino acids, minerals, and vitamins while exhibiting low cholesterol and fat levels, making them highly valuable for consumption [2].

The quality of bamboo shoots is influenced not only by the genetic characteristics of the bamboo species but also by various environmental factors. Recent studies have demonstrated that environmental factors significantly influence the nutritional quality of bamboo shoots [3-5]. Key environmental variables, such as temperature, light, humidity, rainfall, latitude, and altitude, play a crucial role in plant growth and nutrient accumulation. For example, regions situated at higher altitudes typically experience lower temperatures and increased ultraviolet (UV) radiation, which promote the synthesis of secondary metabolites, including flavonoids and phenolics, thereby enhancing nutritional value [6]. Likewise, optimal temperatures ranging from 15 to 25 ℃ and sufficient rainfall facilitate enzyme activity and nutrient transport, essential for bamboo shoots' tenderness and overall quality [7]. Additionally, soil characteristics such as organic matter, nitrogen, phosphorus, and potassium are pivotal for bamboo growth [8]. Studies have also demonstrated that soil organic matter, total porosity, and longitude are the primary factors influencing the nutritional quality of bamboo shoots, with a positive correlation observed between higher soil organic matter and increased nutrient content. Transcriptome analyses reveal that environmental conditions play a crucial role in determining bamboo shoot quality by modulating key metabolic pathways [9]. Environmental factors are

ARTICLE IN PRESS

crucial for plant growth and development and significantly influence the quality of bamboo shoots. Exploring the relationship between these factors and bamboo shoot quality offers valuable guidance for producing high-quality bamboo shoots.

Chimonobambusa rigidula belongs to the family Gramineae and the genus Chimonobambusa. It features culms that range from 2 to 6 meters in height and 1.5 to 3 centimeters in diameter. The internodes measure 10 to 20 centimeters and are characterized by a slightly square or cylindrical shape devoid of hair. This bamboo species is predominantly found in the mountainous regions of southern Sichuan Province, where its distribution significantly overlaps with key giant panda habitats, including the Daxiangling and Qionglai Mountains. Consequently, it serves as a crucial food source for giant pandas. The bamboo shoots typically emerge between September and October, boasting a rich nutritional profile that includes protein, amino acids, fats, carbohydrates, calcium, phosphorus, iron, carotene, and vitamins. These shoots are not only delicious but also highly nutritious.

ARTICLE IN PRESS

The comprehensive impact of environmental factors on the quality of *C. rigidula* bamboo shoots, the extent of their influence, and whether they are the primary determinants of quality variations in shoots of the same bamboo species across different regions remain underexplored. In light of this, the present study builds upon previous research to analyze the relationship between the quality of *C. rigidula* bamboo shoots and environmental factors in various regions. It aims to identify the principal environmental factors affecting the quality of *C. rigidula* bamboo shoots, thereby providing a scientific basis and theoretical support for managing *C. rigidula* and enhancing shoot quality.

2 Materials and methods

2.1 Sample collection area and environmental characteristics

The sampling sites are situated in three distinct regions: Muchuan County (MC), Mabian County (MB), and Pingshan County (PS). The bamboo forests sampled consist exclusively of pure *C. rigidula*, with each region's bamboo forest area measuring no less than 1 hectare (hm^2). All bamboo stands are uniformly 8 years old, and the management approach employed is extensive. These regions were selected as they represent the primary cultivation areas of *C. rigidula* in China. They encompass a diverse range of climatic and geographical conditions, including variations in temperature, rainfall, and soil properties. The meteorological data of the three regions were sourced from the local meteorological bureaus. Further details can be found in Table 1 and 8.

2.2 Experimental material

At each experimental site, we randomly selected and marked 100 bamboo shoots, ensuring their basal diameters were similar in size. Subsequently, bamboo shoots with approximately 10 cm of soil were excavated from each site. These shoots were entirely severed at the culm base, and their external morphology and nutritional components were assessed. The five-point sampling

ARTICLE IN PRESS

method also collected mixed soil samples from the 10~15 cm soil layer from the clumps. These samples were placed in sterile zip-lock bags, labeled accordingly, and transported to the laboratory, where they were air-dried at room temperature to determine soil chemical properties.

2.3 Indicator determination and methods

2.3.1 Determination of bamboo shoot appearance morphology

After excavating the bamboo shoots and removing the soil, we measured the mass (g), length (cm), and basal diameter (cm) of each shoot. Subsequently, the outer shells were peeled off, and the inedible portions at the base of the bamboo shoots were cut away. The bamboo shoots were washed and weighed, and the edible quantity (g) and rate (%) were calculated. Calculate the edible rate according to the following formula.

$$\text{Edible rate} = \frac{\text{total mass-outer shells mass-inedible portion at the base of bamboo shoots mass}}{\text{total mass}} \times 100\% \quad (1)$$

2.3.2 Determination of nutritional components in bamboo shoots

The moisture content of bamboo shoots was assessed using the hot air oven method [10]. The ash content was determined through dry ashing in a muffle furnace at 600 ℃ until a grayish-white ash was produced.

After measuring the external morphology, the bamboo shoots were transported to the laboratory, where they were longitudinally sliced, placed on tin foil, labeled, and then subjected to fixation in an oven at 120 ℃ for 30 minutes. Subsequently, they were dried at a temperature of 70 ℃ until a constant mass was achieved. The

ARTICLE IN PRESS

ARTICLE IN PRESS

dried samples were then crushed and stored in a desiccator to determine nutritional indicators.

Approximately 3 g of extracted bamboo shoot powder is continuously extracted in a Soxhlet extractor for 6 hours using a benzene/ethanol (2:1, v/v) mixture in a water bath maintained at 92 ℃. After extraction, the residue is dried and analyzed for lignin and cellulose content. The method described determines the lignin and cellulose content [11]. About 1 g of the dried powder is added to 12 M H_2SO_4, mixed, and hydrolyzed at room temperature for 4 hours. After hydrolysis, distilled water is added to dilute the H_2SO_4 to a final concentration of 1 M, and the mixture is then heated at 105 ℃ for 1 hour. The solution is cooled and subjected to vacuum filtration through a funnel. The filter is air-dried at 60 ℃ until a constant weight is achieved for lignin measurement. To measure the cellulose content, approximately 1 g of dried powder is mixed with 25 mL of a nitric acid-ethanol solution, heated at 100 ℃ for 1 hour, and then transferred to a funnel. The residual solution is sequentially washed with a nitric acid-ethanol mixture and water. Finally, all mixed solutions are vacuum-filtered and dried at 100 ℃. The cellulose and lignin content (%) is calculated using the formula (1):

$$\frac{m1\text{-}m2}{m0} \times 100\% \qquad (2)$$

where m1 represents the total mass of lignin or cellulose collected in the funnel after oven-drying to a constant weight, m2 is the mass of the empty funnel, and m0 is the mass of the bamboo

ARTICLE IN PRESS

shoot sample. Each treatment is conducted with three biological replicates.

The protein content in bamboo shoots was determined using the Coomassie Brilliant Blue G-250 method [12]. A sample of 1 g of dried bamboo shoots was ground with 2 mL of water and centrifuged at 4000 rpm for 20 minutes at room temperature. The resulting supernatant was diluted to a final volume of 10 mL to obtain the soluble protein solution, which was measured spectrophotometrically at a wavelength of 595 nm. The soluble sugar content in bamboo shoots was assessed using the anthrone method [12]. To extract soluble sugars, 1 g of dried bamboo shoots was combined with 15 mL of water in a test tube, which was then heated in a boiling water bath for 20 minutes. The solution was filtered and diluted to 100 mL, and the soluble sugar content was determined spectrophotometrically at 620 nm.

ARTICLE IN PRESS

To determine the starch content in bamboo shoots, 1 g of the sample was ground and extracted twice with 80% ethanol, followed by two extractions with 52% perchloric acid. The determination was subsequently conducted using the anthrone-sulfuric acid method at a wavelength of 640 nm with a spectrophotometer [13].

The amino acid composition was analyzed using an automatic analyzer (HT-1010, HiTech Innovation, China). Briefly, 0.1 g of the sample was hydrolyzed with 6 M HCl and placed in a sealed tube in an oven at 105 ℃ for 24 hours. After hydrolysis, the sample was eluted with water and subsequently freeze-dried. The analyte was

ARTICLE IN PRESS

then dissolved in 0.02 M HCl prior to injection.

An analysis of the mineral elements selenium (Se), iron (Fe), calcium (Ca), magnesium (Mg), sodium (Na), copper (Cu), zinc (Zn), potassium (K) and manganese (Mn) was conducted on bamboo shoots. The content of these mineral elements was evaluated according to the Chinese standards (GB5009.268-2016). Before the experiment, the bamboo shoots were placed in a freeze-dryer until entirely dehydrated. Approximately 0.5 g of bamboo shoot samples were digested using a microwave digestion system using nitric acid. Subsequently, the digested bamboo shoot samples were placed on an adjustable temperature-controlled hot plate to evaporate the acid and then diluted to a final volume of 25 mL with deionized water. Fe, Ca, Mg, Na, Cu, Zn, K, and Mn concentrations were determined using flame atomic absorption spectrometry, while the Se content was measured using atomic fluorescence spectrometry. All samples were analyzed in triplicate.

The ascorbic acid content was determined following the methodology outlined by Yang et al. [14]. Initially, 1 g of bamboo shoot powder was combined with 5 mL of 5% trichloroacetic acid (TCA), and the mixture was centrifuged at 12,000 × g for 15 minutes. Subsequently, 0.1 mL of the supernatant was extracted and combined with 1 mL of ethanol, 1.9 mL of TCA, 0.5 mL of 0.5% phosphoric acid-ethanol, 1 mL of 0.5% O-phenanthroline-ethanol, and 5 mL of 0.03% $FeCl_3$-ethanol. The resulting mixture was maintained at 30 ℃ for 1 hour. Finally, the ascorbic acid content

ARTICLE IN PRESS

ARTICLE IN PRESS

was quantified by measuring the absorbance of the mixture at 534 nm.

Place 1 g of the sample into a Soxhlet extractor to determine the flavonoid content in bamboo shoots. Add 100 mL of 70% ethanol and a small quantity of $CaCO_3$ and extract for 6 to 8 hours. Subsequently, concentrate the extract under reduced pressure. The resulting concentrate should be washed with ethyl ether and then diluted with 70% ethanol to achieve a final volume of 100 mL, which will serve as the sample solution. After aspirating 1 mL of the sample solution, sequentially add 1 mL of 70% ethanol, 0.3 mL of 5% $NaNO_2$, 0.3 mL of 10% $Al(NO_3)_3$, and 2 mL of 4% NaOH at 6-minute intervals to prepare the mixed solution for analysis. Following a 10-minute incubation period, measure the absorbance at 510 nm using a spectrophotometer. Additionally, prepare a standard solution of 100 μg·mL^{-1} using rutin and 70% ethanol and subsequently dilute it to working concentrations ranging from 0 to 50 μg·mL^{-1} [15].

The sample extract was prepared using methanol and dried bamboo shoot powder, and the tannin content was determined using the Folin-Ciocalteu method [16]. A volume of 0.1 mL of the sample extract was mixed with 7.5 mL of distilled water, followed by adding 0.5 mL of Folin phenol reagent and 1 mL of a 35% sodium carbonate solution. The resulting mixture was diluted to a final volume of 10 mL with distilled water. The mixture was thoroughly shaken and allowed to stand at room temperature for

ARTICLE IN PRESS

30 minutes, after which the absorbance was measured at 725 nm—distilled water served as the blank, replacing the sample extract. A standard curve was constructed using a series of gallic acid standard solutions.

Oxalic acid content was determined using reversed-phase high-performance liquid chromatography (HPLC) [17]. A 0.5-g fresh sample was combined with 2 mL of 0.5 mol·L^{-1} hydrochloric acid and a small quartz sand. The mixture was thoroughly ground into a homogenate and then transferred to a test tube. The test tube was placed in a boiling water bath for 15 to 20 minutes, after which it was shaken well. Upon cooling, 4 mL of distilled water were added, and the mixture was allowed to stand overnight. The homogenate was then filtered through a small funnel into a 50-mL volumetric flask. The residue was washed repeatedly with distilled water until the total volume reached 50 mL. Finally, the solution was filtered through a microporous membrane filter and analyzed using an HPLC (Agilent 1100, USA).

2.3.3 Soil sample collection and testing

The soil pH was analyzed using the method described by Bottomley et al. [18]. The soil organic matter content was determined according to the method outlined by Te et al. [19]. The total nitrogen content was measured following the method proposed by Li et al. [20], while the total phosphorus content was assessed based on the method presented by Kozyrev et al. [21]. Additionally, the soil potassium content was analyzed through inductively coupled

ARTICLE IN PRESS

plasma optical emission spectrometry (ICP-OES, PerkinElmer Optima 8000).

2.4 Data analyses

The results of the analyzed samples are presented as mean ± standard deviation (n = 3), derived from three independent replicate experiments. A p-value of less than 0.05 indicated significant differences between means. Calculations and Principal Component Analysis (PCA) were executed using IBM SPSS Statistics 27 software. Graphs were generated utilizing Origin 2022, and redundancy analysis (RDA) of environmental factors about bamboo shoot quality was performed using Canoco 5.0 software.

ARTICLE IN PRESS

3. Results

3.1 The morphological differences of *C. rigidula* bamboo shoots

The weight, basal diameter, and edible amount of bamboo shoots in the MC and PS regions did not exhibit significant differences ($p>0.05$); however, these parameters were significantly greater than those observed in the MB region ($p<0.05$). Furthermore, bamboo shoots' shoot length and edible rate across the three regions showed no significant differences ($p>0.05$), with an average shoot length of 34.15 cm and an average edible rate of 60.75%. Coefficient of variation analysis revealed that the coefficients of variation for all indicators were below 20%, categorizing them as indicators of weak variation (Table 2).

3.2 Differences in the basic nutritional components of *C. rigidula* bamboo shoots

The determination results of the basic nutritional components of bamboo shoots across three regions are presented in Table 3. The moisture, protein, total flavonoid, and starch content of bamboo shoots exhibited no significant differences among the three regions (p>0.05). Notably, the lignin, ash, ascorbic acid, and tannin contents in the MB region were significantly higher than those in the other two regions (p<0.05). Conversely, the cellulose contents in the MC and PS regions were significantly greater than in the MB region (p<0.05). Furthermore, the soluble sugar content in the PS region was significantly elevated compared to the other two regions. The oxalic acid content in the MC region was significantly higher than in the other two regions. The coefficient of variation analysis revealed that the variability of cellulose, lignin, water, ascorbic acid, protein, oxalic acid, total flavonoids, and starch content was low, with coefficients of variation below 20%, thus categorizing them as indicators of weak variability. In contrast, the coefficients of variation for ash, soluble sugar, and tannin content ranged from 20% to 50%, categorizing them as indicators of moderate variability.

ARTICLE IN PRESS

3.3 Differences in the mineral content of *C. rigidula* bamboo shoots

The mineral content of bamboo shoots across the three regions is presented in Table 4. The bamboo shoots from MC exhibit the highest potassium, sodium, calcium, iron, and zinc levels, significantly surpassing those from the other two regions (p<0.05).

In contrast, the differences in mineral contents between MB and PS are not statistically significant ($p>0.05$). Notably, the copper content in bamboo shoots from PS is the highest ($p<0.05$), while the differences between the other two regions are not significant ($p>0.05$). Furthermore, the magnesium content in bamboo shoots from MB is the highest ($p<0.05$), with no significant differences observed between the other two regions ($p>0.05$). Selenium content was undetected in the bamboo shoots from the three regions. The coefficient of variation analysis revealed low variability for potassium, calcium, zinc, copper, and magnesium contents, all exhibiting coefficients of variation below 20%. In contrast, sodium and iron displayed moderate variability, with coefficients of variation ranging from 20% to 50% (Table 3).

3.4 Differences in the amino acid content of *C. rigidula* bamboo shoots

Table 5 shows that this study identified 18 amino acids, including six essential amino acids for humans. Among these, the bamboo shoots from MB exhibited the highest total content of 16 amino acids, with 11 being significantly higher than those found in bamboo shoots from the other two regions ($p<0.05$). Furthermore, the Asp content in the MC region was significantly greater than in the other two regions. In comparison, the Lys content in bamboo shoots across all three regions showed no significant differences ($p>0.05$). An analysis of the average amino acid content revealed that Glu had the highest concentration in bamboo shoots, followed

ARTICLE IN PRESS

by Ser, with cystine being the least abundant, and Cys not detected. The coefficient of variation analysis indicates significant variability in amino acid content. Except Asp, Thr, Gly, Ala, Leu, Lys, Arg, and Pro, which exhibit weak variation, the contents of other amino acids demonstrate moderate to substantial variability. Notably, the coefficient of variation for Tyr content reaches as high as 58.69%.

3.5 Correlation analysis between nutritional traits of *C. rigidula* bamboo shoots and environmental factors

Table 6 presents the pH levels, organic matter content, total nitrogen, total phosphorus, and total potassium content in soils from three distinct regions. Principal Component Analysis (PCA) was conducted to identify the key quality indices of *C. rigidula* bamboo shoots (Table 7). The first three principal components (PC1, PC2, and PC3) accounted for 81.96% of the total variance, with PC1 contributing 43.35%, PC2 contributing 29.56%, and PC3 contributing 9.06%. The most influential variables for PC1 were Met (loading = 0.965), Tan (loading = 0.941), and Ser (loading = 0.918). For PC2, the most influential variables were K (loading = 0.994), Oa (loading = 0.850), and Fe (loading = 0.831). The most influential variables for PC3 included Cel (loading = 0.621), Lys (loading = 0.582), and Vc (loading = 0.471). These indicators are closely associated with the nutritional value of *C. rigidula* bamboo shoots; therefore, the aforementioned indicators were selected for subsequent correlation analysis. As Fig. 1 shows, the correlation

ARTICLE IN PRESS

ARTICLE IN PRESS

analysis between bamboo shoot quality indicators and environmental factors revealed several significant relationships. The oxalic acid content in bamboo shoots exhibited a significant positive correlation with the altitude of the growing site. Additionally, the minimum temperature in September demonstrated a significant positive correlation with the tannin and serine (Ser) contents in bamboo shoots. Furthermore, the maximum temperature in September also positively correlated with the Vc content. There is a significant positive correlation between soil organic matter content and the cellulose content of bamboo shoots. Conversely, the average temperature in September displayed a significant negative correlation with the potassium content in bamboo shoots.

3.6 The relationship between environmental factors and the quality of *C. rigidula* bamboo shoots

The redundancy analysis results of bamboo shoot quality indicators across three regions, considering environmental factors such as soil and climate, are presented in Fig. 2. The cumulative variation explanation rate for bamboo shoot quality about environmental factors was 90.22%. The first and second ordination axes accounted for 82.74% of the cumulative variation, indicating a significant correlation between the 16 quality indicators and the five environmental factors. The minimum temperature in September emerged as the most influential factor, explaining 60.8% of the total variation, followed by the maximum temperature

ARTICLE IN PRESS

in September (20.4%), total soil phosphorus content (5.3%), soil pH (3.6%), and total soil nitrogen content (0.5%). These findings suggest that the minimum and maximum temperatures in September, along with total soil phosphorus content, soil pH, and total soil nitrogen content, are the five critical factors influencing bamboo shoot quality and should be prioritized in the site selection process for bamboo shoot cultivation.

4 Discussion

4.1 Geographical variation in *C. rigidula* bamboo shoots quality

This study reveals distinct differences in the external morphology of bamboo shoots across three regions, with the weight, basal stem diameter, and edible portion of MB bamboo shoots being lower than those in the other two regions. Significant variations in quality and basal diameter of bamboo shoots of the same variety across different regions contribute to discrepancies in the edible portion, which aligns with previous research findings on other bamboo species [22]. The responses, adaptations, and sensitivities of plant phenotypic traits to varying growth environments differ, and the functional traits of plants in response to environmental changes also vary, resulting in marked intraspecific and interspecific differences in the same phenotypic trait [23]. An analysis of the coefficient of variation indicates that the appearance and morphological indicators of bamboo shoots exhibit weak variation, demonstrating stable traits with minimal changes. Furthermore, the analysis of the appearance and morphology of the

ARTICLE IN PRESS

bamboo shoots suggests that those from MC and PS are superior to those from MB.

The basic nutritional components of bamboo shoots are influenced by factors such as water content, protein, soluble sugars, cellulose, lignin, and tannin, which collectively determine their taste and nutritional value. For an example, the lignin and cellulose content and composition of bamboo shoots vary based on their age and geographical location, which critically influences the mouthfeel and taste of the shoots[24]. Higher levels of water content, soluble sugars, and protein correlate with superior quality, while lower levels of lignin and tannin indicate better quality. Water content is a crucial indicator of tenderness in bamboo shoots, directly impacting their taste and overall quality; thus, increased water content is associated with enhanced flavor[25]. This study reveals that the water content of bamboo shoots across the three studied regions is relatively high and exhibits low variability, suggesting that the water content in these areas is relatively stable. Consequently, water content may not be the primary factor influencing the quality of bamboo shoots. Furthermore, MB bamboo shoots exhibit the lowest cellulose content alongside the highest levels of lignin and tannin; MC bamboo shoots have the least tannin content; while PS bamboo shoots contain the highest amounts of soluble sugars, indicating that bamboo shoots from the MC and PS regions are likely to offer a more favorable taste.

In terms of amino acid content in bamboo shoots, components

ARTICLE IN PRESS

ARTICLE IN PRESS

such as Asp, Glu, Gly play a crucial role in determining their flavor. A higher concentration of these amino acids correlates with an improved flavor profile of bamboo shoots. This study assessed the amino acid content in bamboo shoots from three regions, revealing that the Gly and Glu levels in the bamboo shoots from MB and PS were significantly higher than those from MC, which aligns with the sensory evaluation results. Bamboo shoots are abundant in various amino acids essential for human health, providing necessary nutrients [26]. Additionally, this study identified eight essential amino acids in bamboo shoots, specifically Met, Lys, Thr, Ser, Leu, Ile, Val, and His, which are particularly important for infants and young children. Notably, the Thr concentration in bamboo shoots from MB and PS was significantly greater than that from MC. Furthermore, the levels of all essential amino acids in bamboo shoots from MB were markedly higher than those from the other two regions, indicating the superior quality of bamboo shoots from MB.

The test results indicate that the concentrations of potassium (K), magnesium (Mg), and calcium (Ca) in bamboo shoots from the three regions are notably high. Potassium is a crucial mineral that helps regulate blood pressure, and foods abundant in potassium contribute to maintaining stable blood pressure levels. Calcium serves as an essential component for bone formation, while magnesium plays a protective role for the myocardium. These findings suggest that *C. rigidula* bamboo shoots are rich in mineral

ARTICLE IN PRESS

ARTICLE IN PRESS

elements, which can enhance the body's immune function and improve disease resistance, thereby establishing them as an excellent health-promoting vegetable. Notably, bamboo shoots from the MC region exhibit the highest concentrations of these mineral elements. No selenium was detected in bamboo shoots from all three regions, primarily due to the absence of this element in the local soil.

4.2 The relationship between environmental factors and *C. rigidula* bamboo shoots quality

Soil serves as a crucial medium for plant survival and is a primary source of water, heat, and nutrients essential for plant growth. Numerous studies have established a strong correlation between soil quality and the growth of bamboo shoots [27-29]. This study identifies low and high temperatures in September as the primary environmental factors influencing the nutritional quality of bamboo shoots. Specifically, these temperature extremes correlate significantly with the amino acid content in bamboo shoots, showing positive relationships with Ser and Thr, respectively. Furthermore, low and high temperatures in September are also associated with Vc, starch, and tannins. Research indicates that temperature affects plant growth, development, yield, and quality by influencing the rates of nutrient absorption and assimilation [30-32]. During their growth, plants are influenced by genetic factors and environmental conditions. They adjust and balance various functional traits to form a series of trait combinations in response

ARTICLE IN PRESS

to habitat changes [33, 34]. This study found that the quality of *C. rigidula* bamboo shoots is susceptible to changes in the growing environment. Besides temperature, total soil nitrogen, total phosphorus, and pH significantly explain the variations in bamboo shoot quality across different regions, affecting the nutritional components of the bamboo shoots. The response of bamboo shoot quality to environmental changes results from the combined effects of multiple factors. Plants exhibit varying abilities to absorb and utilize nutrients, and there may be synergistic or antagonistic interactions among different environmental factors, leading to varying degrees of influence on bamboo shoot quality. The mechanisms underlying these effects warrant further in-depth research.

5 Conclusion

This study highlights the significant role of environmental factors in shaping the nutritional composition of *C. rigidula* bamboo shoots. The minimum and maximum temperatures in September, total soil phosphorus content, soil pH, and total soil nitrogen content were identified as key drivers of regional variation in *C. rigidula* bamboo shoot quality. The appearance, morphology, and taste of bamboo shoots from MC and PS are superior to those from MB. Notably, bamboo shoots from MB exhibit the highest content of essential amino acids, while bamboo shoots from MC contain the highest levels of mineral elements. In summary, these findings provide critical insights into the sustainable cultivation of *C.*

ARTICLE IN PRESS

rigidula bamboo shoots, highlighting the significance of region-specific environmental management. Furthermore, the research results present strategies for enhancing the value of *C. rigidula* bamboo shoots by optimizing cultivation practices in response to environmental changes.

Funding

This work was supported by Leshan Engineering Technology Research Center for Innovative Utilization of Feature Plant Resources (TSZW2025-6), Opening Foundation of Key Laboratory of Sichuan Province for Bamboo Pests Control and Resource Development (ZL2019002), Sichuan Science and Technology Program (2024NSFSC2084).

Data availability

All the original data are contained in the supplementary data.

Statement

The bamboo forest from which the bamboo shoots were collected for this study is owned by local farmers, and the collection process was conducted with compensation provided at market prices.

Reference

1. Zhang, Y., et al. Bamboo shoot and its food applications in last decade: An undervalued edible resource from forest to feed future people. *Trends in Food Science & Technology*, 104399 (2024).

2. Choudhury, D., Sahu, J. K., Sharma, G. D. Value addition to

ARTICLE IN PRESS

bamboo shoots: a review. *Journal of Food Science and Technology*, *49*, 407-414 (2012).

3. Chongtham, N., et al. Quality improvement of bamboo shoots by removal of antinutrients using different processing techniques: A review. *Journal of food science and technology*, 1-11(2022).

4. Wang, R., et al. Practices and roles of bamboo industry development for alleviating poverty in China. *Clean Technologies and Environmental Policy*, *23*(6), 1687-1699 (2021).

5. Qian, Y., et al. Environmental drivers and transcriptomic variations shaping Lei bamboo shoots across cultivation regions. *Frontiers in Plant Science*, *16*, 1565665 (2025).

6. Goud, E. L., et al. "Climate change and their impact on global food production," in Microbiome Under Changing Climate. Eds. A. Kumar, J. Singh and L. F. R. Ferreira (Woodhead Publishing), 415–436 (2022).

7. Huang, Y., et al. Integrated metabolomic and transcriptomic analysis reveals the effect of artificial shading on reducing the bitter taste of bamboo shoots. *Horticulturae* 8, 594 (2022).

8. Chu, H., et al. Impact of nitrogen fertilizer application on soil organic carbon and its active fractions in moso bamboo forests. *Forests*, *15*(9), 1483 (2024).

9. Qian, Y., et al. Environmental drivers and transcriptomic variations shaping Lei bamboo shoots across cultivation regions. *Frontiers in Plant Science*, *16*, 1565665 (2025).

10. Singhal, P., et al. Effect of different drying techniques on

ARTICLE IN PRESS

the nutritional, antioxidant and cyanogenic profile of bamboo shoots. *Applied Food Research*, *2*(1), 100036 (2022).

11. Zhang, Z., et al. Comparative analysis of the lignification process of two bamboo shoots stored at room temperature. *Plants*, (10), 1399 (2020).

12. Wang, J., et al. The influence of gamma irradiation on the storage quality of bamboo shoots. *Radiation Physics and chemistry*, *159*, 124-130 (2019).

13. Yang, W. T., et al. Qualitative and quantitative characterization of nutrient content and morphology in seeds of bamboo, rice, and wheat. *Journal of Cereal Science*, *101*, 103273 (2021).

14. Yang, B., et al. Impact of melatonin application on lignification in water bamboo shoot during storage. *Food Chemistry: X*, *13*, 100254 (2022).

15. Indira, A., et al. Assessment of bioactive compound variations and in-vitro and in-vivo antioxidant activity in edible fresh and processed Bambusa nutans shoot through FTIR, GC/MS and HPLC analyses. *Food Chemistry*, *452*, 139552 (2024).

16. Tamilselvi, N., et al. Analysis of total phenols, total tannins and screening of phytocomponents in Indigofera aspalathoides (Shivanar Vembu) Vahl EX DC. *Journal of chemical and pharmaceutical research*, *4*(6), 3259-3262 (2012).

17. Fan, L., et al. Shoot nutrition and flavor variation in two Phyllostachys species: does the quality of edible bamboo shoot

ARTICLE IN PRESS

diaphragm and flesh differ?. *Foods*, *12*(6), 1180 (2023).

18. Bottomley, P. J., et al. Methods of soil analysis, Part 2: Microbiological and biochemical properties (John Wiley & Sons, the Soil Science Society of America) (2020).

19. Te, X., et al. Effect of different planting pattern arrangements on soil organic matter and soil nitrogen content under a maize/soybean strip relay intercropping system. *Frontiers in Plant Science*, *13*, 995750 (2022).

20. Li, M., et al. Total nitrogen stock in soil profile affected by land use and soil type in three counties of mollisols. *Frontiers in Environmental Science*, *10*, 945305 (2022).

21. Kozyrev, R., et al. Total phosphorus and phosphorus forms change in sediments along the Tone River. *Frontiers in Earth Science*, *11*, 1060312 (2023).

22. Feleke, S. Site factor on nutritional content of *Arundinaria alpina* and *Oxytenanthera abyssinica* bamboo shoots in Ethiopia. *Journal of Horticulture and forestry*, *5*(8), 115-121 (2013).

23. Mooney, K. A., et al. Evolutionary trade-offs in plants mediate the strength of trophic cascades. *Science*, *327*(5973), 1642-1644 (2010).

24.Yang, J., et al. Using the major components (cellulose, hemicellulose, and lignin) of Phyllostachys praecox bamboo shoot as dietary fiber. *Frontiers in Bioengineering and Biotechnology, 9,* 669136. (2021)

25. Ma, T., et al. A review of the nutritional composition,

ARTICLE IN PRESS

storage challenges, processing technology and widespread use of bamboo shoots. *Foods*, *13*(22), 3539 (2024)

26. Nongdam, P., et al. The nutritional facts of bamboo shoots and their usage as important traditional foods of northeast India. *International scholarly research notices*, *2014*(1), 679073 (2014).

27. Zhou, X., et al. Response of moso bamboo growth and soil nutrient content to strip cutting. *Forests*, *13*(8), 1293 (2022).

28. Chen, Q., et al. The role of soil chemical properties and microbial communities on Dendrocalamus brandisii bamboo shoot quality, Yunnan Province, China. *Frontiers in Microbiology*, *16*, 1551638 (2025).

29. Nong, J., et al. Optimal fertilizer formulation for maximizing bamboo shoot production while improving soil fertility. *BMC Plant Biology*, *25*(1), 1-19 (2025).

30. Näsholm, T., et al. Uptake of organic nitrogen by plants. *New phytologist*, *182*(1), 31-48 (2009).

31. McAllister, C. H., et al. Engineering nitrogen use efficient crop plants: the current status. *Plant biotechnology journal*, *10*(9), 1011-1025 (2012).

32. Ding, Y., et al. Molecular regulation of plant responses to environmental temperatures. *Molecular plant*, *13*(4), 544-564 (2020).

33. Baraloto, C., et al. Decoupled leaf and stem economics in rain forest trees. *Ecology letters*, *13*(11), 1338-1347 (2010).

ARTICLE IN PRESS

ARTICLE IN PRESS

34. Li, Y., et al. Leaf phenotypic variation of endangered plant Tetracentron sinense Oliv. and influence of geographical and climatic factors. *Journal of Forestry Research*, *32*(2), 623-636 (2021).

ARTICLE IN PRESS

Table 1 Basic information of sampling sites

sampling sites	Abbreviation	Longitude (E)	Latitude (N)	Altitude (m)
Muchuan	MC	103°84′12″	28°84′87″	1280

Mabian	MB	103°47′53″	28°78′67″	1241
Pingshan	PS	103°96′81″	28°74′74″	1237

ARTICLE IN PRESS

Table 2. Morphological traits of *C. rigidula* bamboo shoots

Sampling site	Weight (g)	Shoot length (cm)	Basal diameter (cm)	Edible amount (g)	Edible rate (%)
MC	201.09±4.41a	34.49±1.21a	2.14±0.07a	121.52±2.53a	60.44±1.48a
MB	173.14±4.72	33.25±0.7	1.76±0.0	107.70±5.60	61.82±1.56

	b	3a	9b	b	a
PS	204.20±3.62	34.70±1.0	2.23±0.1	122.64±3.54	60.05±0.91
	a	1a	3a	a	a
Mean	192.81	34.15	2.04	117.29	60.75
CV(%)	8.87	2.29	12.2	7.09	1.56

Compared with the same column, different lowercase letters indicated significant differences between different regions (p<0.05).

ARTICLE IN PRESS

ARTICLE IN PRESS

Table 3. The basic nutritents in *C. rigidula* bamboo shoots from different areas

Sampling site	Cellulose (g·100g^{-1})	Lignin (g·100g^{-1})	AW (%)	Ash (g·100g^{-1})	ASC acid (mg·100g^{-1})	SS (g·100g^{-1})	Protein (g·100g^{-1})	Oxalic acid (mg·100g^{-1})	Tf (mg·1000g^{-1})	Tannin (mg·1000g^{-1})	Starch (g·100g^{-1})
MC	18.83±0.70a	12.60±0.30b	91.53±0.32a	0.91±0.004c	7.90±0.27b	0.35±0.04b	2.68±0.11a	5.37±0.08a	56.83±3.85a	576.33±20.55b	1.02±0.11a
MB	16.00±0.36b	14.67±0.32a	91.83±0.15a	1.37±0.03a	11.77±1.24a	0.31±0.05b	2.65±0.03a	4.28±0.10b	46.87±4.63a	953.33±22.03a	1.14±0.10a
PS	18.07±0.38a	13.06±0.38b	91.43±0.47a	1.00±0.02b	10.15±1.51ab	0.49±0.06a	2.83±0.08a	4.16±0.11b	52.97±5.79a	611.00±7.94b	0.94±0.04a
Mean	17.63	13.44	91.60	1.09	9.94	0.38	2.72	4.60	52.22	713.55	1.03
CV(%)	8.31	8.09	0.22	22.30	19.55	24.66	3.55	14.48	9.62	29.20	9.74

ARTICLE IN PRESS

ARTICLE IN PRESS

Compared with the same column, different lowercase letters indicated significant differences between different regions ($p<0.05$). AW: Moisture content; ASC acid: ascorbic acid; SS: soluble sugar; Tf: Total flavonoid

ARTICLE IN PRESS

ARTICLE IN PRESS

Table 4. The mineral content in *C. rigidula* bamboo shoots from different areas

Sampling site	Potassium (K) (mg·1000g^{-1})	Sodium (Na) (mg·1000g^{-1})	Calcium (Ca) (mg·1000g^{-1})	Iron (Fe) (mg·1000g^{-1})	Zinc (Zn) (mg·1000g^{-1})	Copper (Cu) (mg·1000g^{-1})	Magnesium (Mg) (mg·1000g^{-1})	Selenium (Se) (mg·1000g^{-1})
MC	6226.00±57.00a	2.52±0.34a	382.00±9.85a	4.42±0.30a	11.23±1.03a	2.08±0.10b	208.33±1.53ab	–
MB	5843.00±61.59b	1.59±0.35b	354.33±6.81b	3.36±0.34b	8.77±0.12b	2.23±0.14b	215.33±6.81a	–
PS	4973.67±88.38c	1.74±0.25b	361.33±3.51b	2.94±0.24b	8.64±0.23b	2.86±0.24a	202.00±5.30b	–
Mean	5680.89	1.95	365.89	3.57	9.55	2.39	208.55	
CV(%)	11.30	25.60	3.93	21.34	15.28	17.31	3.19	

ARTICLE IN PRESS

Compared with the same column, different lowercase letters indicated significant differences between different regions ($p<0.05$). —: undetected

ARTICLE IN PRESS

ARTICLE IN PRESS

Table 5. The amino acid content in *C. rigidula* bamboo shoots from different areas

Amino acid ($mg \cdot 100g^{-1}$)	MC	MB	PS	Mean	CV(%)
Asp	19.17±0.78a	15.87±1.12b	14.67±0.51b	16.57	14.06
Thr	14.40±1.06b	20.67±1.46a	18.87±1.70a	17.98	17.96
Ser	31.77±1.61b	50.83±1.27a	32.83±1.85b	38.48	27.84
Glu	80.30±2.01b	153.33±2.31a	162.67±7.57a	132.10	34.14
Gly	5.70±0.79b	8.5±0.20a	7.43±0.45a	7.21	19.60
Ala	24.30±1.91b	29.77±1.43a	23.70±0.10b	25.92	12.90
Val	25.80±0.46b	38.23±1.90a	22.63±1.27c	28.89	28.54
Cystine	1.13±0.23b	2.07±0.12a	2.30±0.10a	1.83	33.81
Met	6.37±0.40c	10.13±0.58a	7.60±0.44b	8.03	23.86
Ile	20.67±1.39b	25.73±2.06a	16.43±0.67c	20.94	22.23
Leu	25.53±0.59b	29.10±0.53a	24.83±2.16b	26.49	8.65
Tyr	15.77±0.42b	41.63±2.63a	17.07±0.85b	24.82	58.69
Pheny	22.57±0.55b	39.80±2.35a	17.83±1.34c	26.73	43.25
GABA	33.30±1.45a	20.87±0.57c	29.87±1.58b	28.01	22.92
Lys	22.70±2.20a	25.13±1.00a	21.50±1.14a	23.11	8.00
His	13.53±1.00c	20.83±0.60a	18.17±0.61b	17.51	21.10
Arg	22.97±1.03b	26.63±2.58a	18.70±0.90c	22.77	17.43
Pro	11.20±1.01b	13.47±0.91a	11.30±0.69b	11.99	10.70

Compared with the same row, different lowercase letters indicated significant differences between different regions ($p<0.05$). Pheny: phenylalanine; GABA: γ-aminobutyric acid

ARTICLE IN PRESS

ARTICLE IN PRESS

ARTICLE IN PRESS

Table 6. Soil indicators from different areas

Sampling site	Soil pH	Soil organic matter (g/kg)	Total soil nitrogen (%)	Total soil phosphorus (g/kg)	Total soil potassium (g/kg)
MC	6.02±0.04a	98.03±2.00a	0.41±0.023a	0.90±0.036b	34.4±1.41a
MB	5.74±0.10b	38.83±0.83b	0.26±0.015b	0.77±0.036c	14.93±0.76c
PS	4.45±0.04c	85.03±1.01c	0.44±0.016a	1.21±0.031a	20.73±1.20b
Mean	5.40	73.96	0.37	0.96	23.35
CV(%)	15.49778	42.07	26.06	23.55	42.81

ARTICLE IN PRESS

ARTICLE IN PRESS

Table 7. Principal component loading matrix in *C. rigidula* bamboo shoots of different quality index

Quality index	PC1	PC2	PC3
Met	0.965	-0.110	-0.079
Tan	0.941	0.101	-0.299
Ser	0.918	0.107	-0.074
Val	0.894	0.354	0.013
Leu	0.794	0.379	0.207
Thr	0.788	-0.486	0.239
Tf	-0.756	0.093	0.200
Vc	0.754	-0.294	0.471
Ca	-0.750	0.460	0.219
Ile	0.705	0.631	0.089
Na	-0.665	0.559	-0.214
Mg	0.611	0.510	-0.154
Lys	0.608	0.434	0.582
K		0.994	-0.048
Cu	-0.143	-0.954	-0.117
Oa	-0.423	0.850	0.085
Fe	-0.393	0.831	-0.045
SS	-0.473	-0.755	-0.118
Zn	-0.581	0.716	-0.223
Sta	0.487	0.358	-0.745
Cel	-0.574	0.041	0.621
Pr	-0.304	-0.515	-0.355
Lig	0.546	-0.068	-0.026
variance contribution rate (%)	43.349	29.556	9.057
cumulative variance contribution rate (%)	43.349	72.905	81.962

Tan: Tannin; SS: Soluble sugar; Lig: Lignin; Cel: Cellulose; Pr: Protein; Ser: Serine; Thr: Threonine; Val: Valine; Met: Methionine; Lys: Lysine; Leu: Leucine; Ile: Isoleucine; Vc: ascorbic acid; Oa: Oxalic acid; Tf: Total

ARTICLE IN PRESS

flavonoid; Sta: Starch;

Table 8. Climate indicators for 2024 from different areas

Sampling site	MAT (℃)	AAR (mm)	RH (%)	SAT (℃)	STmin (℃)	Stmax (℃)	SPr (mm)
MC	13.8	1353.2	79	21.7	10.4	32.2	159.3
MB	14.6	1289.6	81	22.1	12.0	33.6	167.8
PS	14.6	817.2	77	23.0	10.6	33.1	85.2

SPr: September precipitation; MAT: Mean annual temperature; AAR: Average annual rainfall; RH: Relative humidity of 2024; SAT: September average temperature; STmin: September minimum temperature; STmax: September maximum temperature

ARTICLE IN PRESS

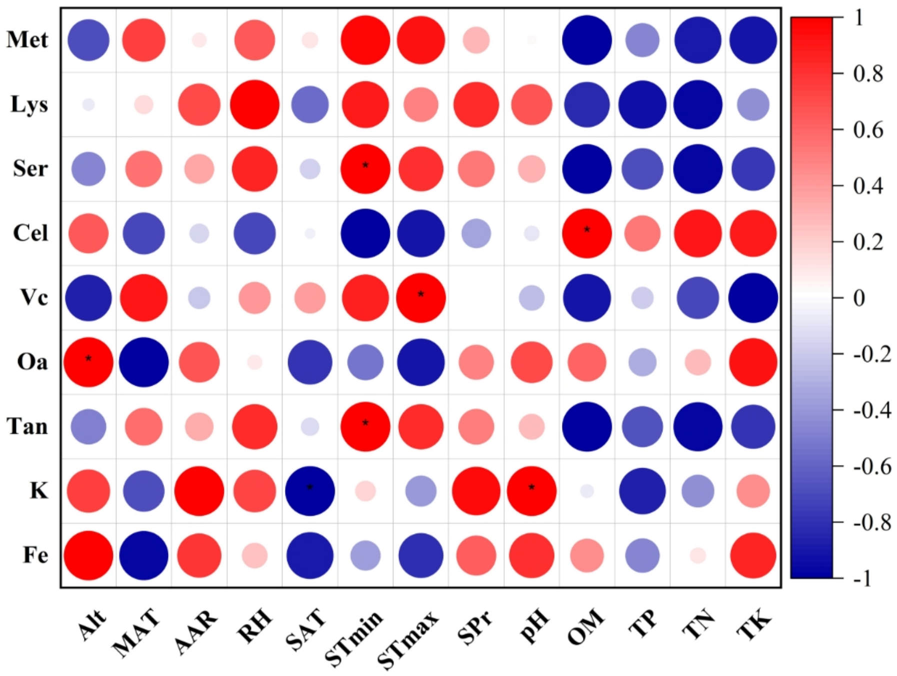

Fig.1 Correlation analysis between the nutritional qualities of *C. rigidula* bamboo shoots and environmental factors across cultivation sites. *: $p<0.05$ Tan: Tannin; Cel: Cellulose; Ser: Serine; Met: Methionine; Lys: Lysine; Vc: ascorbic acid; Oa: Oxalic acid; pH: Soil pH; OM: Soil organic matter; TN: Total soil nitrogen; TP: Total soil phosphorus; TK: Total soil potassium; SPr: September precipitation; Alt: Altitude; MAT: Mean annual temperature; AAR: Average annual rainfall; RH: Relative humidity; SAT: September average temperature; STmin: September minimum temperature; STmax: September maximum temperature

ARTICLE IN PRESS

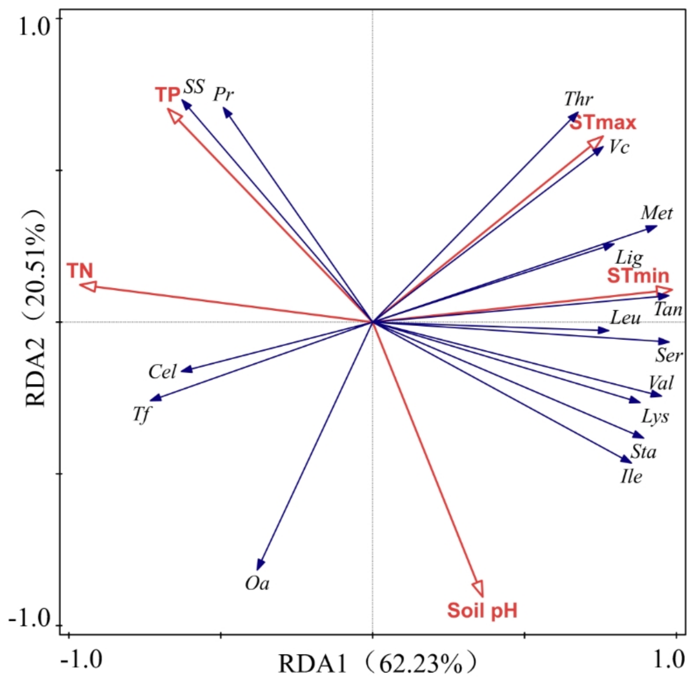

Fig.2 RDA analysis of environmental factors and nutritional quality of *C. rigidula* bamboo shoots.

Tan: Tannin; SS: Soluble sugar; Lig: Lignin; Cel: Cellulose; Pr: Protein; Ser: Serine; Thr: Threonine; Val: Valine; Met: Methionine; Lys: Lysine; Leu: Leucine; Ile: Isoleucine; Vc: ascorbic acid; Oa: Oxalic acid; Tf: Total flavonoid; Sta: Starch; pH: Soil pH; TN: Total soil nitrogen; TP: Total soil phosphorus; STmin: September minimum temperature; STmax: September maximum temperature

ARTICLE IN PRESS