

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

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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 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. 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.

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 °C 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. Environmental factors are 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 species is predominantly found in the mountainous regions of southern Sichuan Province, China. In addition, *C. rigidula* is also a type of bamboo favored by 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.

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 (hm²). 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. Further details can be found in Table 1.

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

2.2 Experimental material

Bamboos exhibiting similar growth conditions, were randomly selected as study samples from various research sites. 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 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 (kg), length (cm), and basal diameter (cm) of each shoot. Subsequently, the outer shells were peeled off, and the inedible lower portions were cut away. The bamboo shoots were washed and weighed, and the edible quantity (kg) and rate (%) were calculated.

2.3.2 Determination of nutritional components in bamboo shoots

The moisture content of bamboo shoots was assessed using the hot air oven method. The ash content was determined through dry ashing in a muffle furnace at 600 °C until a grayish-white ash was produced ⁹.

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 °C for 30 minutes. Subsequently, they were dried at a temperature of 70 °C until a constant mass was achieved. The 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 °C. After extraction, the residue is dried and analyzed for lignin and cellulose content. The method described determines the lignin and cellulose content ¹⁰. About 1 g of the dried powder is added to 12 M H₂SO₄, mixed, and hydrolyzed at room temperature for 4 hours. After hydrolysis, distilled water is added to dilute the H₂SO₄ to a final concentration of 1 M, and the mixture is then heated at 105 °C for 1 hour. The solution is cooled and subjected to vacuum filtration through a funnel. The filter is air-dried at 60 °C 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 °C 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 °C. The cellulose and lignin content (%) is calculated using the formula (1):

$$\frac{m1 - m2}{m0} \times 100\%$$

1

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 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 (Wang et al., 2019). 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 ¹¹. 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.

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 ¹².

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 °C for 24 hours. After hydrolysis, the sample was eluted with water and subsequently freeze-dried. The analyte was 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. ¹³. 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% FeCl₃-ethanol. The resulting mixture was maintained at 30 °C for 1 hour. Finally, the ascorbic acid content 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 CaCO₃ 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% NaNO₂, 0.3 mL of 10% Al(NO₃)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 ¹⁴.

The sample extract was prepared using methanol and dried bamboo shoot powder, and the tannin content was determined using the Folin-Ciocalteu method ¹⁵. 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 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) ¹⁶. 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. ¹⁷. The soil organic matter content was determined according to the method outlined by Te et al. ¹⁸. The total nitrogen content was measured following the method proposed by Li et al. ¹⁹, while the total phosphorus content was assessed based on the method presented by Kozyrev et al. ²⁰. Additionally, the soil potassium content was analyzed through inductively coupled 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, as determined by one-way analysis of variance (ANOVA). Calculations 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.

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).

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 ± 4.72b	33.25 ± 0.73a	1.76 ± 0.09b	107.70 ± 5.60b	61.82 ± 1.56a
PS	204.20 ± 3.62a	34.70 ± 1.01a	2.23 ± 0.13a	122.64 ± 3.54a	60.05 ± 0.91a
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 ($p < 0.05$).

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 20–50%, categorizing them as indicators of moderate variability.

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 20–50% (Table 3).

Table 3
The basic nutrients 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
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											

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 ± 351b	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	
Compared with the same column, different lowercase letters indicated significant differences between different regions ($p < 0.05$). –: undetected								

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 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%.

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

Amino acid (mg·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 (<i>p</i> < 0.05). Pheny: phenylalanine; GABA: γ-aminobutyric acid					

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

As Fig. 1 shows, the correlation analysis between bamboo shoot quality indicators and environmental factors revealed several significant relationships. Notably, the oxalic acid content in bamboo shoots exhibited a significant positive correlation with the altitude of the growing site. Moreover, the relative air humidity in September showed a significant positive correlation with the isoleucine (Ile) content. Additionally, the minimum temperature in September demonstrated a significant positive correlation with the tannin and serine (Ser) contents in bamboo shoots. The maximum temperature in September also positively correlated with the vitamin C (Vc) and threonine (Thr) content. Conversely, the rainfall in September displayed a significant negative correlation with the protein content in bamboo shoots.

Furthermore, the soil organic matter content revealed a significant negative correlation with lignin content and a significant positive correlation with cellulose content. The soil phosphorus content exhibited a significant positive correlation with the soluble sugar content in bamboo shoots. In contrast, the soil nitrogen content was significantly negatively correlated with the leucine (Leu) and valine (Val) contents, and the soil potassium content demonstrated a significant negative correlation with the threonine (Thr) content.

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; 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

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 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.

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

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 species²¹. 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 trait²². 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 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. 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. 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 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 nutrients²³. 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 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.

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

Soil and the external environment serve as critical sources of nutrients for plants, which adapt to these conditions through transpiration, litterfall, and root exudates^{24,25}. 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^{26–28}. 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 to habitat changes^{29,30}. 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. 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.

Declarations

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Author Contribution

F contributed to the manuscript writing, provided financial support, and conducted sample testing. C contributed to the manuscript writing, provided financial support. LF was responsible for sample collection and testing. LG also engaged in sample collection and testing. G handled the data analysis. Z oversaw financial support, managed funding, designed experiments, and reviewed the manuscript. All authors reviewed the manuscript.

Data Availability

All the original data are contained in the supplementary data.

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Figures

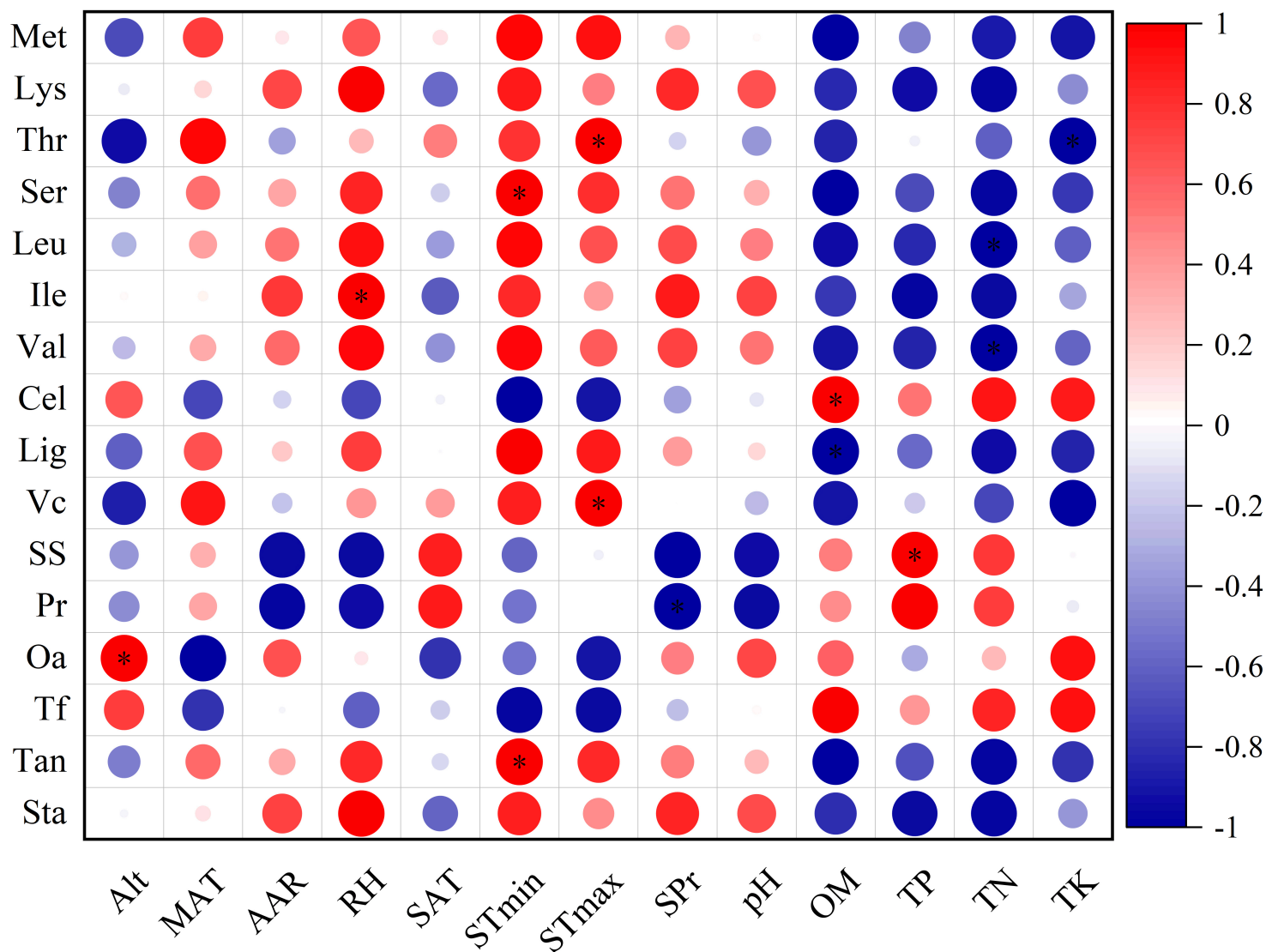


Figure 1

Correlation analysis between the nutritional qualities of *C. rigidula* bamboo shoots and environmental factors across cultivation sites. *: $p < 0.05$

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; 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

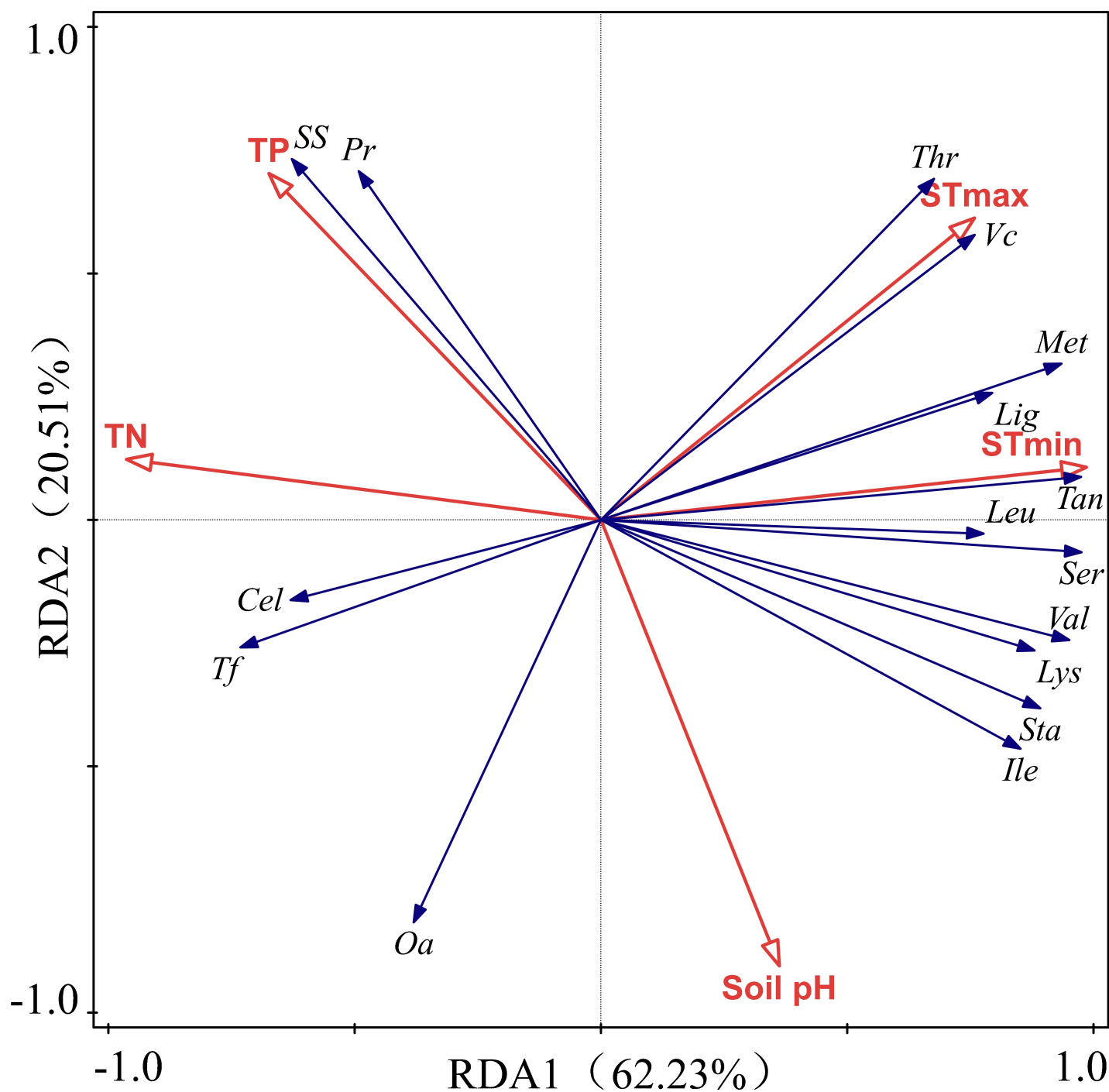


Figure 2

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

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