Effects of Different Climates and Soil Environments in the Yanshan Production Area on the Growth and Quality of Chestnuts

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Abstract [**Objectives**] This study conducted investigations on the climate and soil nutrients of different chestnut orchards in the Yanshan region, selected key ecological factors affecting the growth and fruit quality of chestnuts, and provided a theoretical basis for the cultivation, introduction, and scientific planting of high-quality chestnuts. [**Methods**] The 'Yanshanzaofeng' chestnuts in four orchards located in Qianxi, Qianan, Funing, and Qinglong of Hebei Science and Technology Normal University were selected. The climate and soil nutrient conditions of the four orchards were investigated. Growth indicators such as branch length and diameter, nut weight, and internal quality indicators such as starch, fat, and protein content were analyzed. Principal component analysis was conducted on nine climate factors and twelve soil factors in the four chestnut orchards to identify the most closely related ecological factors influencing chestnut growth and quality. [**Results**] (i) Different orchards had varying climate conditions, with Qianan orchard having higher rainfall than the others, Funing orchard having the highest number of sunshine hours in the growing season, and Qinglong orchard experiencing the greatest temperature difference during the growing season. (ii) Significant differences were found in soil nutrient content among the orchards, with the coefficient of variation for organic matter and mineral elements ranging from 19.1% (S) to 80.3% (available phosphorus). (iii) The main ecological factor influencing chestnut growth was the photosynthetic factor, while fruit quality was influenced by a combination of climatic factors, photosynthetic factors, and nutrient factors. Key ecological factor indicators included: annual precipitation, annual sunshine hours, growing season precipitation, growing season sunshine hours, soil organic matter, available phosphorus, available potassium, alkali nitrogen, copper, zinc, available boron, and sulfur. Soluble solids were significantly positively correlated with growing season sunshine hours, and fat was significantly positively correlated with available potassium and alkali nitrogen, and significantly positively correlated with available phosphorus. [**Conclusions**] Orchards with high growing season precipitation, long sunshine hours, and high organic matter and nitrogen-phosphorus-potassium content in the soil are more conducive to promoting the growth of 'Yanshanzaofeng' chestnuts and improving fruit quality.

Key words Chestnut; Ecological factors; Fruit quality; Principal component analysis
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The chestnut (*Castanea mollissima* Bl.), a member of the *Castanea* genus in Fagaceae, is one of the important woody grain tree species in China[1]. Chestnuts are rich in nutrients, have a wide cultivation range, strong adaptability, and high ecological and economic value[2]. In 22 provinces, autonomous regions, and municipalities directly under the central government of China, chestnuts are grown as an important economic crop[3]. Currently, China ranks first in the world in terms of total planting area and production of chestnuts[4]. Different cultivation environments significantly impact the growth and fruit quality of chestnuts. Only by planting suitable varieties in suitable locations can maximize benefits be achieved. However, improper introduction in chestnut cultivation often leads to a decrease in chestnut quality[5]. Therefore, understanding the impact of climatic conditions and soil nutrients on the growth and fruit quality of chestnuts and identifying key ecological factors affecting chestnut quality, is of great significance for chestnut introduction and scientific cultivation.

In addition to being influenced by their own genetic characteristics, the growth of tree bodies and the quality of fruit are greatly affected by climate and soil. Wei *et al.* [6] studied the impact of ecological factors on the phenotypic characteristics of Juglans regia in Tibet and found that the annual average precipitation and annual average temperature significantly affected the thickness of the fruit pulp. Wei *et al.* [7] studied the quality of Red Delicious apples in different ecological regions and found a close relationship between fruit quality and climatic factors, with factors such as single fruit weight being influenced by precipitation, sunshine hours, and relative humidity. Yao *et al.* [8] studied the key factors affecting the quality of hazelnuts and identified sunshine hours as one of the key influencing factors. Liu *et al.* [9] studied the relationship between soil nutrients and the quality of chestnuts, finding a positive correlation between soil organic matter, total nitrogen, effective zinc, and chestnut quality. Zu *et al.* [10] studied the impact of different soil conditions on the quality of *Citrus sinensis* and found a highly significant positive correlation between soil organic matter content, soluble solids, and vitamin C content. Hader Yisake *et al.* [11] studied the differences in quality of *Ziziphus jujuba* under different soil conditions and found variations in the content of soluble sugars and soluble solids in *Ziziphus jujuba* fruits grown in

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three types of soil. Previous studies have mostly focused on analyzing the impact of soil types, soil nutrients, or climate on chestnut quality individually. There is a lack of comprehensive analysis of the combined effects of climate and soil nutrients on the growth and fruit quality of chestnuts. The interactive effects of climate conditions and soil conditions on chestnut quality are still not fully understood.

Chestnut cultivation is widespread in China, with a variety of chestnut species. The climate and soil conditions vary in different cultivation areas, making it impossible for the same variety to achieve consistent quality across all cultivation areas. Matching the right tree to the right land is an important way to address the blind introduction of chestnuts and promote scientific cultivation. Therefore, in this study, the relationship between chestnut growth and fruit quality with climate and soil factors was investigated and key ecological factors influencing chestnut growth and fruit quality were identified to aim to provide a theoretical basis for the scientific cultivation of chestnuts.

Materials and Methods

Overview of the Experimental Site

The 'Yanshanzaofeng' chestnut orchards in the four cultivation areas (counties) of Qianan, Qianxi, Funing, and Qinglong in Hebei Province were selected as the experimental subjects. The distribution of chestnut orchards in each location is shown in Table 1.

Table 1 Basic information of chestnut orchards

Number	Location	Longitude	Latitude	Elevation//m	Topography	Aspect	Position on slope	Planting density (m×m)
1	Qianan	118.86	40.12	114	Low hills and ridges	East-facing slope	Upslope	4×5
2	Qianxi	118.37	40.21	160	Low hills and ridges	South-facing slope	Upslope	3×3
3	Funing	119.29	39.92	36	Low hills and ridges	South-facing slope	Upslope	4×4
4	Qinglong	118.72	40.42	358	Low hills and ridges	South-facing slope	Upslope	4×5

Source of meteorological data

The meteorological data from various regions are sourced from local meteorological stations as well as the meteorological data provided by China Weather Network for the months of January to December 2023 (http://www.weather.com.cn). Statistical analysis and organization were conducted on nine meteorological indicators for each region, with growing season-related indicators calculated for the months of June to August.

Experimental design

In each 'Yanshanzaofeng' cultivation area, one chestnut orchard with consistent terrain, topography, and cultivation management practices was selected. Fifteen chestnut trees with moderate vigor, free from pests and diseases, and bearing normal fruit were randomly selected from each orchard. From April 17 to 19, ten trees were selected in an S-shaped pattern in each trial garden as soil sampling points. Soil samples were collected from the 0-60 cm soil layer in eight directions. The soil samples from each point were mixed, and 1 kg of soil sample was selected using the quartering method, air-dried, ground, and sieved for measuring soil nutrient content. During the maturation period, 30 chestnut burrs were collected from the east, west, south, and north directions on the periphery of the canopy, stored for one month, and then the chestnut quality indicators were measured. During the dormancy period, the growth of various types of branches was assessed, and twenty normal fruiting branches, vegetative branches, and fruiting branches growing normally on the periphery of the canopy were selected for length and diameter measurements.

Methods for determining various indicators

Methods for determining soil nutrients The method of determining soil nutrient content referred to Shidan Bao[12]. Organic matter was determined using the potassium dichromate sulfuric acid method; effective nitrogen was determined using the NaOH hydrolysis diffusion method; available phosphorus was determined using the molybdenum antimony anti-colorimetric method; available potassium was determined using the ammonium acetate flame photometry method. The ASI method was used to determine the levels of macro and micronutrients in the soil. Copper, iron, manganese, and zinc were extracted using the ASI extraction solution (0.25 mol/L $NaHCO_3$ + 0.01 mol/L EDTA + 0.01 mol/L NH_4F); available boron and sulfur were extracted with a 0.08 mol/L calcium phosphate solution; available calcium and magnesium were extracted with 1 mol/L KCl. The filtrate was measured using an atomic absorption spectrophotometer.

Methods for determining chestnut growth indicators During the dormant period, the growth of various types of branches was assessed by selecting mature trees with normally growing fruiting branches, vegetative branches, and biennial bearing branchesat the periphery of the canopy. Calipers were used to measure the diameter at the midpoint of 20 fruiting branches, vegetative branches, and biennial bearingbranches, with the unit in millimeters and accuracy to 0.1 mm. Length was measured using a meter ruler, measuring the length of 20 fruiting branches, vegetative branches, and biennial bearing branches in centimeters, with the unit in centimeters and accuracy to 0.1 cm.

Methods for determining chestnut quality indicators Moisture Content: The determination was conducted following the GB/T 5009.3-2003 *Determination of Moisture in Foods*. Thirty randomly selected, uniformly mixed chestnuts were shelled, and the kernels were individually weighed. They were then placed in an oven at 105 ℃ for 0.5 h to fix the color, followed by drying at 80 ℃ to a constant weight. The dried samples were ground into powder with a grinder, sieved through a 100-mesh sieve, and stored in sealed bags as the test samples for chestnut quality indicators. Each measurement was repeated three times. Fat content was determined by Soxhlet extraction method according to the GB/T 5009.6-2016 *Determination of Fat in Foods*. Protein content was determined using the Kjeldahl method. Soluble sugar content was determined by the anthrone-sulfuric acid colorimetric method. Starch content was determined by the UV-visible spectrophotometry method. Soluble solids content was measured using a refractometer with a PAL-1 digital refractometer [13-16].

Data analysis

Excel 2016 was employed for data organization, and calculation of the mean, standard deviation, and coefficient of variation for each indicator. Multivariate statistical analysis was conducted using SPSS 26.0, including examination of differences by the Duncan multiple comparison test, correlation analysis using the Pearson method, and principal component analysis to reduce dimensionality of ecological factors.

Results and Analysis

Analysis of climate differences in different cultivation areas

There were differences in climate conditions among the different cultivation areas (Table 3). The average monthly precipitation was highest in Qianan (64.45 mm), followed by Qianxi (54.95 mm) and Funing (54.16 mm), with Qinglong being the lowest (50.25 mm). The average temperature was highest in Funing (14.42 ℃) and lowest in Qinglong (12.73 ℃). The annual precipitation was highest in Qianan (708.90 mm), followed by Qianxi (604.40 mm) and Funing (595.80 mm), with Qinglong being the lowest (552.70 mm). The growing season precipitation was highest in Qianan (539.20 mm), significantly higher than other three cultivation areas, with Qinglong being the lowest (392.90 mm). The average temperature during the growing season was highest in Funing (26.03 ℃) and lowest in Qinglong (24.87 ℃). The sunshine hours during the growing season were highest in Funing (728.10 h), followed by Qianxi and Qianan, with Qinglong having the lowest (689.50 h). Qinglong had the largest temperature difference during the growing season (21.70 ℃), while Funing had the smallest (19.30 ℃).

Analysis of differences in soil nutrients among different orchards

The soil nutrient conditions in different chestnut orchards were significantly different, with significant differences in various nutrient indicators (Table 2). The average contents of organic matter, effective nitrogen, available phosphorus, available potassium, available boron, available calcium, copper, manganese, zinc, iron, magnesium, and sulfur in the soil of four chestnut orchards were 11.33 g/kg, 86.58, 15.21, 85.56, 0.43 mg/kg, 0.41 g/kg, 57.47, 740.10, 114.415 mg/kg, 48.51, 9.34, and 0.13 g/kg, respectively. The coefficient of variation for each indicator ranged from 19.1% (sulfur) to 80.3% (available phosphorus). The soil in Qianxi had the highest content of available calcium, manganese, and iron, while the soil in Qian'an had the highest content of effective nitrogen, available potassium, and magnesium. The soil in Funing had the highest content of available phosphorus, copper, zinc, and sulfur, and the soil in Qinglong had the highest content of organic matter and available boron. According to the correlation analysis of soil nutrients (Fig. 1), organic matter was significantly positively correlated with effective nitrogen, available boron, and sulfur; available phosphorus was significantly positively correlated with zinc and sulfur, positively correlated with available potassium, significantly negatively correlated with manganese, and negatively correlated with iron and available calcium; available potassium was significantly positively correlated with effective nitrogen, significantly negatively correlated with manganese, iron, and available calcium; effective nitrogen was significantly positively correlated with magnesium, significantly negatively correlated with iron, copper, and manganese; copper was significantly positively correlated with zinc, significantly negatively correlated with magnesium; manganese was significantly positively correlated with iron and available calcium; zinc was significantly positively correlated with sulfur, significantly negatively correlated with magnesium; iron was significantly positively correlated with available calcium; sulfur was significantly positively correlated with available boron, significantly negatively correlated with available calcium; and available boron was significantly negatively correlated with available calcium.

Table 2 Climate characteristics of different cultivation areas

Cultivation Area	Qianxi	Qianan	Funing	Qinglong
Average monthly precipitation//mm	54.95	64.45	54.16	50.25
Annual average temperature//℃	14.25	13.85	14.42	12.73
Average monthly sunshine hours//h	212.27	217.34	214.04	211.05
Annual precipitation//mm	604.40	708.90	595.80	552.70
Annual sunshine hours//h	2 335.00	2 390.70	2 354.40	2 321.60
Growing season precipitation//mm	429.80	539.20	456.40	392.90
Growing season average temperature//℃	25.83	25.70	26.03	24.87
Growing season sunshine hours//h	695.50	693.20	728.10	689.50
Growing season temperature difference//℃	20.70	20.30	19.30	21.70

Table 3 Nutrient characteristics of soil in different chestnut orchards

Cultivation area	Qianxi	Qianan	Funing	Qinglong	Mean value	Coefficient of variation//%
Soil organic matter OM//g/kg	6.20 ±0.11 d	13.05 ±0.50 b	11.48 ±0.42 c	14.58 ±1.40 a	11.33	28.6
Effective nitrogen EN//mg/kg	35.80 ±1.13 c	131.90 ±10.26 a	84.58 ±7.78 b	94.05 ±10.15 b	86.58	41.0
Rapidly available phosphorus RP//mg/kg	5.28 ±0.03 c	13.07 ±0.18 b	31.12 ±1.24 a	11.38 ±1.55 b	15.21	80.3
Rapidly available potassium RK//mg/kg	28.38 ±0.65 d	131.81 ±3.82 a	119.68 ±8.57 b	62.36 ±5.91 c	85.56	49.7
Rapidly available boron RB//mg/kg	0.17 ±0.01 d	0.37 ±0.01 c	0.50 ±0.03 b	0.66 ±0.04 a	0.43	44.0
Rapidly available calcium RCa//g/kg	0.72 ±0.04 a	0.30 ±0.02 bc	0.27 ±0.02 c	0.33 ±0.04 b	0.41	70.7
Copper Cu//mg/kg	69.79 ±3.57 b	23.43 ±0.56 d	88.02 ±10.43 a	48.62 ±4.81 c	57.47	43.1
Manganese Mn//mg/kg	1 079.37 ±89.52 a	556.67 ±24.23 c	434.67 ±44.55 d	897.71 ±57.87 b	740.10	38.6
Zinc Zn//mg/kg	88.21 ±3.10 b	60.09 ±2.48 c	215.90 ±20.46 a	92.39 ±5.45 b	114.15	76.2
Iron Fe//g/kg	66.11 ±2.53 a	31.52 ±0.11 d	38.94 ±1.83 c	57.47 ±3.66 b	48.51	31.2
Magnesium Mg//g/kg	7.96 ±0.65 c	12.17 ±0.24 a	7.51 ±0.53 c	9.71 ±1.45 b	9.34	27.6
Sulphur S//g/kg	0.11 ±0.01 c	0.12 ±0.01 bc	0.16 ±0.01 a	0.14 ±0.02 ab	0.13	19.1

The data in the table are presented as mean ± standard deviation. Duncan's one-way analysis of variance was used, and different lowercase letters represent significant differences among chestnut quality indicators under different chestnut orchards, the same below.

Analysis of differences in chestnut growth and quality traits in different cultivation areas

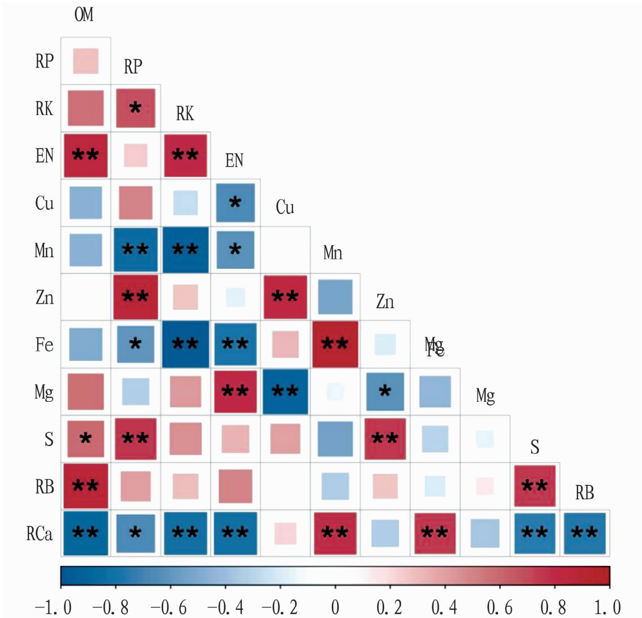
Analysis of the differences in chestnut growth and fruit quality traits in different chestnut cultivation areas (Table 4) revealed significant differences in chestnut growth and fruit quality among the different cultivation areas. The number of fruiting branches per biennial bearing branch in Qianxi (2.77) and Qian'an (2.81) was significantly higher than that in Funing (1.72) and Qinglong (1.74); the moisture content was highest in Qian'an (52.18%), significantly higher than in Qianxi (50.06%) and Qinglong (48.56%); the soluble protein content was highest in Qinglong (0.79%), significantly higher than in Qian'an (0.66%) and Funing (0.61%); the fat content was highest in Qian'an (2.75%), significantly higher than in other cultivation areas; and Funing had the highest soluble solids content (29.87%), significantly higher than in other cultivation areas. However, the fruiting branch length in Funing (29.37 cm) was significantly lower than in other regions; Qianxi had the highest fruitingbranch diameter (6.32 mm), significantly higher than Qian'an (4.97%) and Qinglong (5.21%); the biennial bearing branch was the highest in Qinglong (94.65 cm), and the lowest in Funing (67.83 mm); among them, single grain weight, bract number per fruit branch, soluble sugar content, starch content, nutritional branch length, nutritional branch diameter, and biennial bearing branch diameter showed no significant differences among the four cultivation areas. The coefficient of variation for various chestnut indicators ranged from 3.3% (moisture content) to 35.4% (fat), indicating that fat content has the greatest variability, with weaker genetic stability, while the moisture content of chestnut kernels shows relatively good genetic stability under different growing conditions.

Selection of key ecological factors influencing chestnut growth and quality

Principal component analysis was conducted on 21 ecological factors in four chestnut cultivation areas. As shown in Table 5, the eigenvalues of the first three principal components were all greater than 1, with a cumulative variance contribution rate of 98.08%, indicating that the first three principal components could reflect the majority of the original ecological factor information. The variance contribution rate of the first principal component was 40.17%. The indicators with relatively large characteristic vectors included average monthly precipitation, average monthly sunshine hours, annual precipitation, annual sunshine hours, and growing season precipitation, with the absolute value of the characteristic vectors reflecting their importance in the principal component. It suggested that the first principal component could be classified as a climatic factor. The second principal component was mainly influenced by indicators such as growing season sunshine hours, available phosphorus, copper, and zinc, primarily reflecting plant photosynthetic conditions, indicating that the second principal component could be classified as a photosynthetic factor. The third principal component was significantly influenced by indicators such as soil organic matter, available potassium, effective nitrogen, available boron, and sulfur, which could be classified as nutrient factors. In summary, the key ecological factors affecting chestnut quality could be categorized into climatic factors, photosynthetic factors, and nutrient factors. These factors included annual precipitation, annual sunshine hours, growing season precipitation, growing season sunshine hours, soil organic matter, available phosphorus, available potassium, effective nitrogen, copper, zinc, available boron, and sulfur.

Correlation analysis of chestnut growth, fruit quality, and key ecological factors

Correlation analysis was conducted between chestnut growth indicators, fruit quality indicators, and key ecological factors. From Fig. 2, it can be observed that the moisture content was significantly positively correlated with annual sunshine hours, growing season precipitation, and available potassium, and significantly positively correlated with annual precipitation; fat content was significantly positively correlated with annual sunshine hours, available potassium, and effective nitrogen, and significantly positively correlated with growing season precipitation, soil organic matter, and available phosphorus; soluble solids content was significantly positively correlated with growing season sunshine hours, and positively correlated with copper; fruiting branch

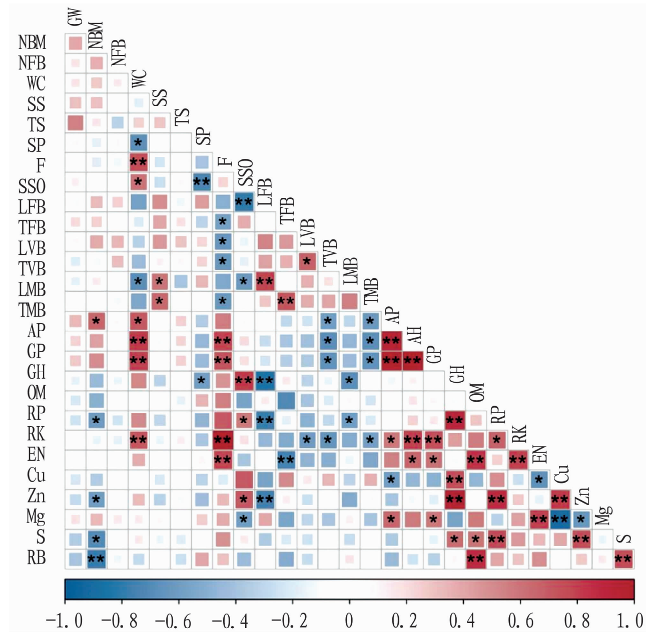


OM. Soil organic matte; RP. rapidly available phosphorus; RK. rapidly available potassium; EN. effective nitrogen; Cu. copper; Mn. manganese; Zn. zinc; Fe. iron; Mg. magnesium; S. sulphur; RB. rapidly available boron; RCa. rapidly available calcium.

Red indicates a positive correlation between factors, with stronger positive correlations appearing as a deeper shade of red; blue indicates a negative correlation between factors, with stronger negative correlations appearing as a deeper shade of blue. $^{*}P\leqslant0.05$, $^{**}P\leqslant0.01$.

Fig. 1 Correlation analysis of various indicators in the soil of different chestnut orchards

length was significantly negatively correlated with growing season sunshine hours, available potassium, and zinc; fruiting branch diameter was significantly negatively correlated with soil organic matter and effective nitrogen; nutritional branch diameter was significantly negatively correlated with annual sunshine hours, growing season precipitation, and available potassium; biennial bearing branch length was significantly negatively correlated with growing season sunshine hours; and biennial bearing branch diameter was significantly negatively correlated with annual sunshine hours, growing season precipitation, and effective nitrogen.



GW. Single grain weight; NBM. number of fruiting branches per biennial bearing branch; NFB. number of fruits per fruiting branch; WC. water content; SS. soluble sugar; TS. total starch; SP. soluble protein; F. fat; SSO. soluble solid; LFB. length of fruiting branch; TFB. diameter of fruiting branch; LVB. length of vegetative branch; TVB. diameter of vegetative branch; LMB. length of biennial bearing branch; TMB. diameter of biennial bearing branch; AP. annual precipitation; AH. annual sunshine hours; GP. growing season precipitation; GH. growing season sunshine hours; OM. soil organic matter; RP. rapidly available phosphorus; RK. rapidly available potassium; EN. effective nitrogen; Cu. copper; Zn. zinc; S. sulphur; RB. rapidly available boron.

Fig. 2 Correlation analysis of chestnut growth, fruit quality, and key ecological factors

Table 4 Growth and fruit quality traits of chestnuts in different chestnut orchards

Cultivation area	Qianan	Qianxi	Funing	Qinglong	Mean value	Coefficient of variation//%
Single grain weight//g	8.00±0.48 a	8.00±0.50 a	7.66±0.41 a	7.60±0.44 a	7.82	5.6
Number of fruiting branches per biennial bearing branch	2.77±0.08 a	2.81±0.34 a	1.72±0.24 b	1.74±0.27 b	2.26	26.3
Number of fruits per fruiting branch	2.29±0.19 a	2.36±0.20 a	2.19±0.47 a	2.24±0.31 a	2.27	12.1
Water content//%	52.18±0.70 a	50.06±0.54 b	52.00±0.93 a	48.56±0.31 c	50.70	3.3
Soluble sugar//%	9.63±1.32 a	9.76±2.13 a	8.72±1.95 a	9.95±1.27 a	9.52	16.2
Total starch//%	50.20±3.74 a	49.19±10.88 a	48.26±11.74 a	44.54±2.85 a	48.05	15.5
Soluble protein//%	0.66±0.07 b	0.67±0.08 ab	0.61±0.04 b	0.79±0.04 a	0.68	12.4
Fat//%	2.75±0.02 a	1.09±0.04 d	2.64±0.06 b	1.65±0.06 c	2.03	35.4
Soluble solid//%	27.03±0.83 c	28.40±0.35 b	29.87±0.35 a	25.43±0.45 d	27.68	6.4
Length of fruiting branch//cm	39.14±2.76 a	39.73±5.82 a	29.37±1.86 b	43.42±2.38 a	37.92	16.4
Diameter of fruiting branch//mm	4.97±0.19 b	6.32±0.56 a	5.62±0.59 ab	5.21±0.35 b	5.53	12.0
Length of vegetative branch//cm	23.98±2.87 a	35.82±14.71 a	23.19±1.58 a	29.61±3.78 a	28.15	30.1
Diameter of vegetative branch//mm	3.68±0.10 a	4.95±0.96 a	4.27±0.31 a	4.88±0.81 a	4.45	17.3
Length of biennial bearing branch//cm	78.47±11.42 ab	84.33±12.19 ab	67.83±2.98 b	94.65±8.18 a	81.32	15.9
Diameter of biennial bearing branch//mm	10.27±0.84 a	12.99±1.76 a	11.84±1.68 a	12.86±1.12 a	11.99	13.8

Table 5 Principal component analysis of ecological factors

Ecological factors	Principal component		
	PC1	PC2	PC3
Average monthly precipitation	0.975	-0.145	-0.157
Annual average temperature	0.372	0.689	-0.613
Average monthly sunshine hours	0.993	0.104	0.043
Annual precipitation	0.975	-0.145	-0.157
Annual sunshine hours	0.993	0.104	0.043
Growing season precipitation	0.997	0.050	-0.031
Growing season average temperature	0.459	0.695	-0.546
Growing season sunshine hours	0.026	0.995	0.085
Growing season temperature difference	-0.484	-0.863	0.132
Soil organic matter	0.144	-0.181	0.971
Rapidly available phosphorus	0.133	0.877	0.443
Rapidly available potassium	0.751	0.370	0.538
Effective nitrogen	0.647	-0.177	0.732
Copper	-0.542	0.786	-0.253
Manganese	-0.574	-0.594	-0.516
Zinc	-0.227	0.946	0.199
Iron	-0.814	-0.321	-0.450
Magnesium	0.630	-0.621	0.366
Sulphur	-0.185	0.576	0.729
Rapidly available boron	-0.303	0.019	0.952
Rapidly available calcium	-0.324	-0.245	-0.908
Eigenvalue	9.13	6.20	5.27
Variance contribution rate//%	40.17	30.83	27.07
Cumulative contribution rate//%	40.17	71.01	98.08
Weight coefficient	0.41	0.31	0.28

PC1, PC2, and PC3 represent the eigenvalues of the first principal component, the second principal component, and the third principal component, respectively.

Discussion

There were differences in climate conditions among the four chestnut cultivation areas. Qian'an had the highest annual precipitation, average monthly precipitation, and growing season precipitation, while Qinglong had the lowest. Water plays an important role in the growth and development of chestnuts. Water shortage and drought can severely inhibit photosynthesis and cause serious damage to the trees[17]. The annual average temperature and growing season average temperature were highest in Funing and lowest in Qinglong. During the chestnut fruit enlargement period, temperatures above 20 ℃ can promote nut growth[18]. Funing had the highest number of sunshine hours during the growing season, while Qinglong had the lowest. Chestnuts are light-loving tree species, and sufficient sunlight is beneficial to their growth and development. Inadequate sunlight during the chestnut fruit enlargement period can inhibit fruit growth[19]. Qinglong had the largest temperature difference during the growing season, while Funing had the smallest. The larger the temperature difference during the growing season, the smaller the individual nut quality of chestnuts[20].

The differences in soil nutrient characteristics among the four chestnut cultivation areas were significant. The coefficient of variation of soil organic matter and mineral element content was the smallest for sulfur (19.1%), indicating that the sulfur content in the soils of the four Yanshanzaofeng cultivation areas studied was relatively stable. The coefficient of variation of available phosphorus content was the largest (80.3%), with Funing having the highest available phosphorus content and Qianxi the lowest. The coefficient of variation of available calcium content was also relatively high (70.7%), with Qianxi having the highest and Funing the lowest. It is similar to the results of the second national soil survey in China, where Tangshan soil is rich in calcium carbonate, while Qinhuangdao soil has much lower calcium content. The phosphorus content in Qinhuangdao soil is about three times that of Tangshan soil. Correlation analysis of soil nutrients in different cultivation areas showed that organic matter was significantly positively correlated with effective nitrogen and available boron, and significantly positively correlated with sulfur. It indicates that increasing soil organic matter content plays a positive role in improving the availability of nutrients such as boron and sulfur in the soil, thereby promoting the growth and development of chestnuts. It is similar to the findings of previous studies by Yao *et al.*[21] and Yu *et al.*[22]. Available phosphorus was significantly positively correlated with available potassium, indicating a certain relationship between the various elements in the soil, consistent with the results of Zhang *et al.*[23]. Effective nitrogen was significantly positively correlated with magnesium, significantly negatively correlated with iron and available calcium, and significantly negatively correlated with copper and manganese. It demonstrates the synergistic interactions among trace elements in the soil, collectively influencing the growth and fruit quality of chestnuts, consistent with previous research findings[24].

Different cultivation areas have different climate and soil conditions, which also affect the growth and fruit quality of chestnuts. Fan *et al.*[20] found that climatic conditions such as large temperature differences, high temperatures, and long sunshine hours during the chestnut growing season promoted the sweetness and stickiness of chestnut fruit. In different soil types, Zhang *et al.*[25] found that chestnuts grown in brown soil conditions had better quality compared to those grown in yellow soil conditions. The correlation analysis conducted in this study between chestnut growth and fruit quality indicators and key ecological factors revealed that soluble solids content was significantly positively correlated with growing season sunshine hours, with sunshine hours being a key factor influencing the soluble solids content of the fruit[26]. Fat content was significantly positively correlated with available potassium and effective nitrogen, and significantly positively correlated with available phosphorus. Nitrogen-phosphorus-potassium combined application can effectively increase the fat content of chestnuts[27].

Conclusions

The climate conditions vary among different chestnut cultivation orchards. The annual and seasonal precipitation in Qian'an chestnut orchard are higher than the other three orchards. The growth season sunshine duration is highest in Funing chestnut orchard, reaching 728.1 hours, while Qinglong chestnut orchard has the largest temperature difference during the growth season, which is 21.7 ℃.

There are significant differences in soil nutrient content among different chestnut cultivation orchards. The coefficient of variation for organic matter and mineral elements in the soil ranges from 19.1% (S) to 80.3% (available phosphorus). Qianxi chestnut orchard has the highest content of available calcium, manganese, and iron in the soil. Qian'an chestnut orchard has the highest content of alkali nitrogen, available potassium, and magnesium in the soil. Funing chestnut orchard has the highest content of available phosphorus, copper, zinc, and sulfur in the soil. Qinglong chestnut orchard has the highest content of organic matter and available boron in the soil.

Through principal component analysis of 21 ecological factors, 12 main ecological factor indicators that influence chestnut growth and nut quality were selected. They are annual precipitation, annual sunshine duration, growth season precipitation, growth season sunshine duration, soil organic matter, available phosphorus, available potassium, alkali nitrogen, copper, zinc, available boron, and sulfur. Correlation analysis between chestnut growth, nut quality, and key ecological factors revealed that the soluble solid content of chestnut nuts is significantly positively correlated with the growth season sunshine duration. The fat content of chestnut nuts is significantly positively correlated with soil available potassium and alkali nitrogen, and positively correlated with available phosphorus.

In conclusion, orchards with high growth season precipitation, long sunshine duration, and high organic matter, nitrogen, phosphorus, and potassium content in the soil are more conducive to promoting chestnut tree growth and improving nut quality.

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