

Article

Correlation analysis of soil nutrient and quality index in pepper planting areas

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Abstract: This study explores the correlation between soil nutrient elements and pepper fruit quality in Guizhou Province, highlighting regional variations in nutrient influence. Guizhou, with its unique mountainous and karst terrain, provides a distinct ecological environment for pepper cultivation. Our analysis of three major pepper-growing regions—Dafang, Guiyang, and Zunyi—demonstrates that nitrogen, phosphorus, and potassium levels in the soil significantly impact pepper quality. Potassium plays a particularly vital role in fruit development, as deficiencies in potassium often result in flower and fruit drop and reduced yield. In Dafang, AP (available phosphorus) and TK (total potassium) were most closely linked to amino acids, reducing sugars, and capsaicinoid content, while in Bozhou, SAN (available nitrogen) was most influential, and in Qingzhen, TP (total phosphorus) and AK (available potassium) were predominant. The findings suggest that key soil elements, such as available phosphorus, available potassium, available nitrogen, and organic matter, influence the quality indicators—amino acids, reducing sugars, capsaicin, and dihydrocapsaicin—in pepper fruits. Further analysis indicates that Guizhou's distinct soil composition significantly contributes to its peppers' unique flavor profile. The combined effects of soil nutrients, pepper varieties, and cultivation practices underline the superior quality of Guizhou peppers. This study provides a foundation for understanding the soil-quality interaction and enhances the market recognition of Guizhou's pepper varieties. Future research should investigate the integrated effects of environmental and soil factors to better assess Guizhou's favorable growth conditions for peppers.

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Keywords: pepper; different regions; soil nutrients; fruit quality; correlation analysis; Random forest regression

1. Introduction:

Pepper (*Capsicum annuum* L.), part of the Solanaceae family, is one of the most important economic crops in Guizhou Province's. With a long history of cultivation and rapid industrial growth, peppers have significantly contributed to local prosperity [1]. These peppers are rich in essential nutrients, such as capsaicinoids, capsanthin esters, vitamins, carotenoids, phenolic compounds, and various trace elements [2]. Moreover, compounds like pepper pigments and capsaicin have valuable industrial applications, including in food, feed, cosmetics, military, and pharmaceuticals [3]. By 2023, the pepper cultivation area in Guizhou had reached 5.2 million hm², with an expected production of 7.7 million tons. The planting industry generated over 30 billion yuan, and the processing industries added an additional 16 billion yuan, benefiting approximately 1.4 million pepper farmers annually [4].

The unique mountainous climate of Guizhou has given rise to many high-quality pepper varieties. Historically, Dafang Wrinkled Pepper has been praised as “Guizhou Wrinkled Pepper,” “Tribute Pepper,” and “The Pride of Peppers” [5]. The distinct climate and soil of Zunyi impart a strong aroma, unique flavor, and moderate spiciness to its peppers, with Xiazi Town emerging as the largest pepper trading hub in China and Asia [6].

Understanding the relationship between regional characteristics, such as soil quality, and pepper quality is key to improving Guizhou pepper's brand recognition, boosting market competitiveness, and promoting sustainable regional economic development.

The quality of crop fruits is largely shaped by environmental factors, particularly soil conditions. For example, the soluble sugar and vitamin C content in seedless longan fruits is linked to soil phosphorus, potassium, nitrogen, and potassium levels [7]. Likewise, peach quality is strongly influenced by soil copper, calcium, phosphorus, organic matter, and the pH of the root zone [8].

Variations in regional and seasonal factors, soil environments, climate, and cultivation practices may significantly impact the nutritional quality of peppers. However, existing research on Guizhou peppers mainly focuses on germplasm resources or specific quality traits, with little attention to regional differences. Additionally, there is insufficient scientific evidence to support the superior quality of Guizhou peppers. This study thus focuses on three prime pepper-growing regions—Dafang, Guiyang, and Zunyi—to analyze the relationship between soil nutrient characteristics and pepper fruit quality, aiming to provide scientific evidence for the high nutritional value and excellent taste of Guizhou peppers, and to further enhance their brand image and market recognition.

2. Materials and Methods

2.1. Experimental Materials

All hot pepper varieties were come from four sources: those bred by the Guizhou Academy of Agricultural Sciences, the Zunyi Academy of Agricultural Sciences, local pepper varieties from Guizhou, and commercial pepper varieties. A total of 31 different pepper varieties were chosen, representing three distinct fruit shapes: upright pepper (Chaotianjiao), long pepper (Xianjiao), and pearl pepper (Zhuzijiao) (presented in Table 1).

Table 1. Sample Information.

Number	Variety	type	Number	Variety	type
1	Qianjiao 4	Xianjiao	18	Suilajiao 1	Chaotianjiao
2	Qianla 11	Xianjiao	19	Xingsu Single	Chaotianjiao
3	Qianjiao 11	Xianjiao	20	Guinong Single	Chaotianjiao
4	Qianla 3	Chaotianjiao	21	Dafang Xianjiao	Xianjiao
5	Chuanjiao 112	Xianjiao	22	Suiyang Chaotianjiao	Chaotianjiao
6	Changla 7	Xianjiao	23	Huaxi Pepper	Xianjiao
7	Chuanjiao 19	Xianjiao	24	Huangyang Xiaomila	Chaotianjiao
8	Qianla 9	Zhuzijiao	25	Zunyi Chaotianjiao	Chaotianjiao
9	Qianla 10	Zhuzijiao	26	Huangping Xianjiao	Xianjiao
10	Layan 12	Xianjiao	27	Meijiang Pear l	Zhuzijiao
11	Hongla 18	Xianjiao	28	Lafuomei	Xianjiao
12	Shanbao 1	Chaotianjiao	29	Bolajiao 15	Xianjiao
13	Shanbao 2	Chaotianjiao	30	Xiuting	Xianjiao
14	Layan 3	Chaotianjiao	31	Niuchang Pepper	Xianjiao
15	Qianjiao 5	Xianjiao			
16	Chaotianjiao 8	Chaotianjiao			
17	Chaotianjiao 6	Chaotianjiao			

2.2. Methodology and Sample Collection

All pepper seedlings were sown between March 15 and 30, 2022, using floating seedling technology. The seedlings were transplanted in May to three experimental sites in [Guizhou Province](#): Qingzhen City (Guiyang), Dafang County (Bijie), and Bozhou District

(Zunyi). Each variety was planted in an area of approximately 200 m². The soil was well-prepared, classified as yellow soil, and had moderate fertility. Fertilization and management followed local conventional practices. Mature red fruits were harvested around mid-September for quality testing. (Table 2)

Table 2. Basic Information of Pepper Planting Areas.

Area	Longitude and latitude	Elevation	pH value	SOM(g/kg)	TN (g/kg)	TP (g/kg)	TK (g/kg)	SAN(mg/kg)	AP (mg/kg)	AK (mg/kg)
Dafang	N: 27°04' E: 105°80'	1860 m	5.94	22.71	1.49	0.80	16.20	74.24	50.32	352.59
Bozhou	N: 27°53' E: 106°71'	848 m	6.05	21.88	1.34	0.99	12.90	77.91	24.01	128.44
Qingzhen	N: 26°18' E: 106°19'	1201 m	6.12	13.80	0.73	1.05	18.90	31.61	24.31	183.85

During the pepper fruit maturation period, 20 uniformly growing pepper plants were selected, and mature, disease-free fruits from the third and fourth layers were collected. The fruits were then divided into three random groups and immediately transported to the Pepper Research Laboratory of the Guizhou Academy of Agricultural Sciences for quality analysis.

Simultaneously, soil samples were taken from the 0–20 cm depth at the root zone of the pepper plants. The soil samples were mixed, large stones and debris were removed, and the samples were sieved through a 200-mesh sieve. After air-drying, the samples were analyzed in the laboratory for pH, organic matter (SOM), total nitrogen (TN), total phosphorus (TP), total potassium (TK), alkali-hydrolyzable nitrogen (SAN), available phosphorus (AP), and available potassium (AK).

2.3. Indicators and Measurements

Soil nutrient measurements: Organic matter (SOM) was determined by potassium dichromate oxidation with external heating. pH was measured using an electrode method. Total nitrogen (TN) was assessed by sulfuric acid digestion using the Kjeldahl method. Alkali-hydrolyzable nitrogen (SAN) was measured using the alkali-hydrolyzable diffusion method. Total phosphorus (TP) was determined by sodium hydroxide fusion and molybdenum-antimony colorimetry, while available phosphorus (AP) was measured using the Olsen method. Total potassium (TK) and available potassium (AK) were measured by sodium hydroxide fusion and flame photometry.

Fruit quality measurements: Fruit quality indicators were determined following the methods of Zhou Peng et al.[10]. Reducing sugars were measured according to the instructions provided with the assay kits, amino acids were determined similarly, and capsaicin and dihydrocapsaicin levels were quantified using high-performance liquid chromatography (HPLC) as per the GB/T 21266–2007 national standard.

2.4. Data Analysis

Data was processed using Excel 2010 for preliminary organization, followed by descriptive statistical analysis in DPS. Correlation and path analysis, as well as scientific plotting, were performed using Origin 2020. Random forest models were constructed using the R.3.5.2 package “Random Forest,” which enabled the calculation of the importance of different soil factors on quality indicators.

3. Results and Analysis

3.1. Analysis of Soil Nutrient Characteristics in Different Pepper-Growing Regions

The analysis of soil nutrient content in different pepper-growing regions is presented in Table 3. The pH values of the soils in the three regions ranged from 4.98 to 7.64. Among these, Qingzhen had the highest average pH value of 6.3, with a pH range of 5.18 to 6.85, indicating acidic soil. The pH values in Dafang ranged from 5.00 to 6.60, while those in Bozhou ranged from 4.98 to 7.64. There were no significant differences in the average pH between Dafang and Bozhou. The coefficient of variation (CV) for pH was largest in Bozhou (0.12), followed by Qingzhen (0.08) and Dafang (0.07), suggesting that the pH in Bozhou was more influenced by pepper varieties.

Table 3. Descriptive statistical characteristics of soil nutrient content in different area.

Item		pH value	SOM(g/kg)	TN (g/kg)	TP (g/kg)	TK (g/kg)	SAN(mg/kg)	AP (mg/kg)	AK (mg/kg)
Da fang	Avg	6.01b	21.54c	1.40 c	0.75 c	16.40 a	117.32 c	6.40 b	294.36 a
	Min	5.35	18.48	1.25	0.55	14.64	66.10	3.52	146.28
	Max	6.60	25.85	1.67	0.99	18.29	188.98	14.90	479.15
	Std Dev	0.42	1.87	0.11	0.09	0.95	30.83	2.53	109.55
	CV	0.07	0.09	0.08	0.12	0.06	0.26	0.40	0.37
Bo zhou	Avg	5.85 b	32.79 b	2.20 b	1.61 a	13.65 b	149.31 b	25.73 a	116.87 c
	Min	5.04	26.86	1.80	1.25	12.25	122.00	4.31	74.00
	Max	7.01	47.22	3.37	2.75	15.13	214.21	55.47	164.00
	Std Dev	0.68	4.47	0.34	0.36	0.67	19.22	14.12	18.83
	CV	0.12	0.14	0.15	0.22	0.05	0.13	0.55	0.16
Qingzh en	Avg	6.35a	62.09a	3.03 a	1.09 b	13.13 c	234.49 a	10.03 b	176.20 b
	Min	5.18	54.20	2.74	0.67	10.97	185.87	2.50	101.99
	Max	6.85	68.26	3.33	1.29	14.94	307.88	34.32	297.91
	Std Dev	0.48	3.14	0.11	0.12	0.79	26.44	7.14	55.55
	CV	0.08	0.05	0.04	0.11	0.06	0.11	0.71	0.32

Note: Different lowercase letters in the same column indicates significant difference at 0.05level.

There were substantial differences in soil nutrient content across the three regions. Organic matter content ranged from 18.48 to 68.26 g/kg, with Qingzhen having the highest average value (62.09 g/kg) and Dafang the lowest (21.54 g/kg). Total nitrogen content ranged from 1.25 to 3.31 g/kg, with Qingzhen showing the highest average value (3.03 g/kg) and Dafang the lowest (1.4 g/kg). Total phosphorus content ranged from 0.55 to 2.75 g/kg, with Bozhou having the highest average value (1.61 g/kg) and Dafang the lowest (0.75 g/kg). Total potassium content ranged from 10.97 to 18.29 g/kg, with Dafang having the highest average value (14.4 g/kg) and Qingzhen the lowest (13.13 g/kg). Alkali-hydrolyzable nitrogen content ranged from 66.61 to 307.88 mg/kg, with Qingzhen showing the highest average value (234.49 mg/kg) and Dafang the lowest (117.32 mg/kg). Available phosphorus content ranged from 2.5 to 55.47 mg/kg, with Bozhou having the highest average value (25.73 mg/kg), while the other two regions did not show significant differences. Available potassium content ranged from 74 to 419.15 mg/kg, with Dafang having the highest average value (294.36 mg/kg) and Bozhou the lowest (116.87 mg/kg).

The coefficient of variation (CV), which reflects the degree of dispersion of the variables, indicated that the CV for available phosphorus exceeded 30% in all three regions, suggesting that pepper varieties had a substantial impact on available phosphorus. The variation in available phosphorus was greatest in Qingzhen, with a CV of 71%. Similarly, available potassium showed significant variation, with Dafang displaying the highest CV (37%), indicating a strong influence of pepper varieties on available potassium. Principal component analysis (PCA) of soil nutrient content revealed clear differences among the

three regions, which could be related to differences in fertilization practices and management levels across the regions. (Figure 1)

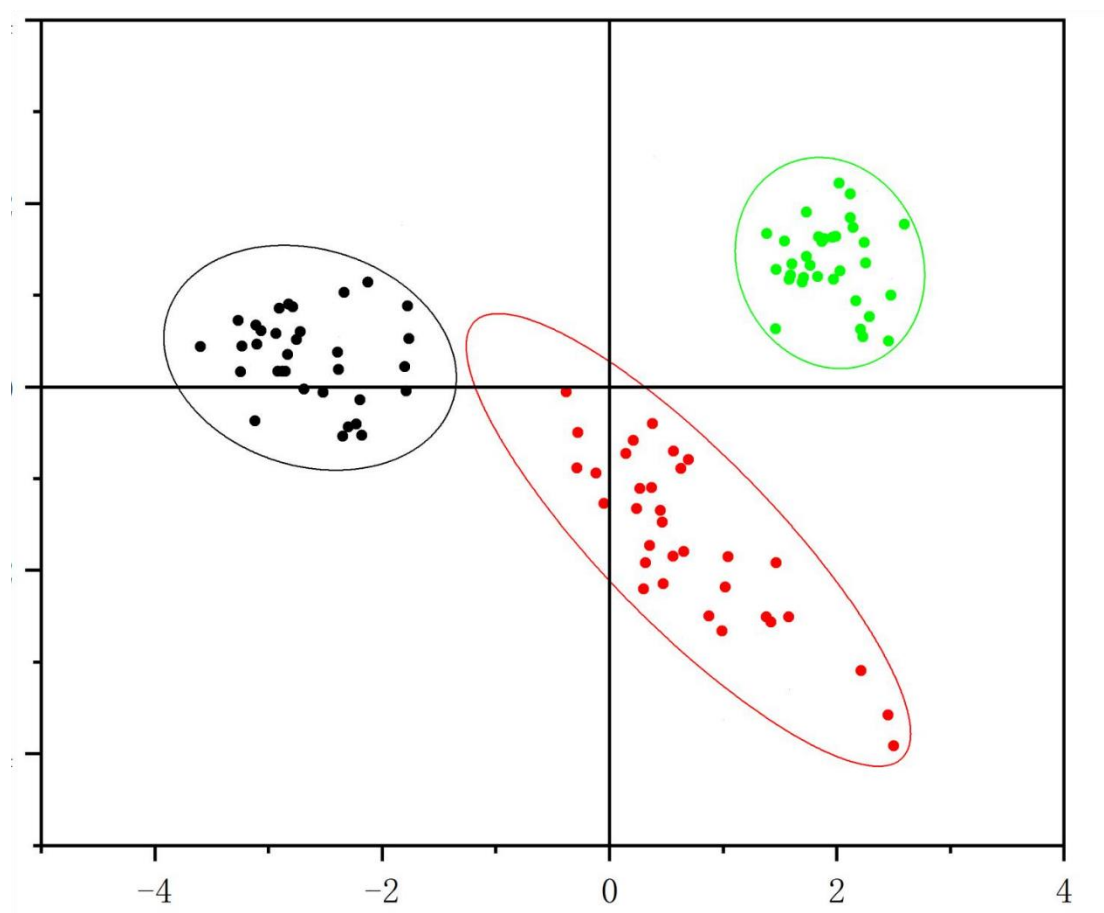


Figure 1. PCA diagram based on oil nutrient content in different regions.

3.2. Analysis of Pepper Quality Indicators in Different Regions

The quality indicators of 31 pepper varieties grown in three different regions were analyzed (Figure 2). Significant differences were observed in the content of reducing sugars, amino acids, capsaicin, and dihydrocapsaicin among the regions. Amino acid content ranged from 23.06 to 60.96 $\mu\text{mol/g}$, with Bozhou showing a significantly higher average amino acid content (43.89 $\mu\text{mol/g}$) compared to the other two regions. No significant differences in amino acid content were found between Dafang and Qingzhen. The content of reducing sugars did not differ significantly among the three regions, ranging from 8.06 to 17.85 g/kg. Capsaicin content ranged from 0.11 to 6.38 g/kg, with Qingzhen showing a significantly higher average content (1.93 g/kg) than the other two regions. The dihydrocapsaicin content ranged from 0.11 to 3.42 g/kg, with Qingzhen having the highest average content (1.07 g/kg), while no significant differences were found in capsaicin and dihydrocapsaicin content between Dafang and Bozhou.

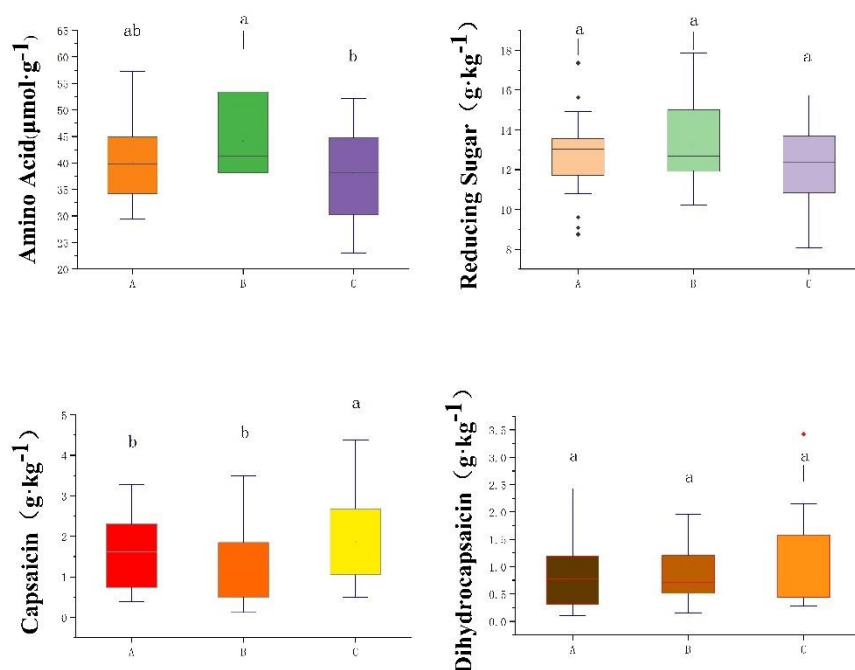


Figure 2. Changes in (A)DaFang, (B)BoZhou (C)QingZhen in fruit quality of different area. Lower-case letters indicate significant difference among the inoculated treatments at $p < 0.05$.

3.3. Correlation Analysis Between Pepper Quality and Soil Nutrient Characteristics

The correlation analysis between soil nutrient characteristics and pepper fruit quality across regions is shown in Figure 3. In Dafang, amino acid content in pepper fruits was significantly negatively correlated with soil pH ($p < 0.05$) and significantly positively correlated with TP(total potassium) ($p < 0.05$) and AP(available phosphorus)($p < 0.05$). No significant correlations were observed between reducing sugars, capsaicin, dihydrocapsaicin, and soil nutrients. In Bozhou, reducing sugar content was significantly negatively correlated with TP(total potassium) content in the soil ($p < 0.05$), while amino acids, capsaicin, and dihydrocapsaicin showed no significant correlation with soil nutrient indicators. In Qingzhen, amino acids in pepper fruits were significantly positively correlated with TP(total phosphorus)($p < 0.05$), while reducing sugars were significantly negatively correlated with AP(available potassium) content in the soil ($p < 0.05$). Dihydrocapsaicin was significantly positively correlated with AP(available phosphorus) and AP(available potassium), whereas capsaicin showed no significant correlation with soil nutrient content. These results suggest that there is a certain degree of correlation between pepper fruit quality indicators and soil nutrients in different regions, with substantial variation in the nature of these correlations across regions.

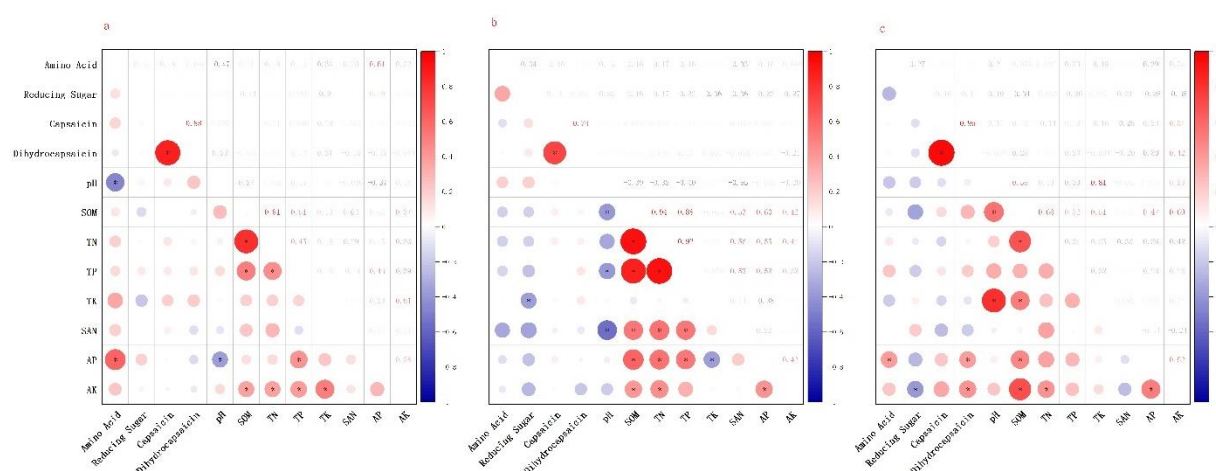


Figure 3. (a)DaFang' heat map of correlation between fruit quality and Descriptive statistical characteristics of soil. (b)BoZhou' heat map of correlation between fruit quality and Descriptive statistical characteristics of soil. (c)QingZhen' heat map of correlation between fruit quality and Descriptive statistical characteristics of soil. *indicates $p < 0.05$, while blank spaces represent non-significant correlations. The larger the circle's diameter, the stronger the correlation; smaller diameters indicate weaker correlations. Red represents positive correlations, while blue indicates negative correlations.

3.4. Analysis of the Impact of Soil Factors on Amino Acids

The relative importance of various soil factors on the quality indicator of amino acids in pepper fruits was further analyzed using a random forest model (Figure 4). As shown, pH, AP (available phosphorus), and TK (available potassium) had the highest contributions with pH being the most important variable in the model, exhibiting significant importance (***) (Figure 4a). This indicates that in the Dafang region, pH has a very significant impact on amino acid levels. SOM (soil organic matter) also plays a significant role on the quality indicator of amino acids. The relative importance of TP (total phosphorus) and TN (total nitrogen) is lower, indicating that their influence on amino acids is relatively minor. While, it also shows that in the Bozhou region, TN (total nitrogen) and SOM (soil organic matter) have significant relative importance for amino acids (Figure 4b). However, with an $R^2=0.25$, the model's explanatory power is relatively low, accounting for only 25% of the variability in the target variable. It can be seen that in the Qingzhen region, TP (total phosphorus), AP (available phosphorus), and pH have significant relative importance on amino acids, while AK (available potassium), SOM, and SAN (available nitrogen) also contribute to the model but with lower relative importance (Figure 4c). Overall, Figure 4 indicates that pH, available phosphorus, available potassium, and organic matter in the soil have the most significant impact on amino acid content in pepper fruits.

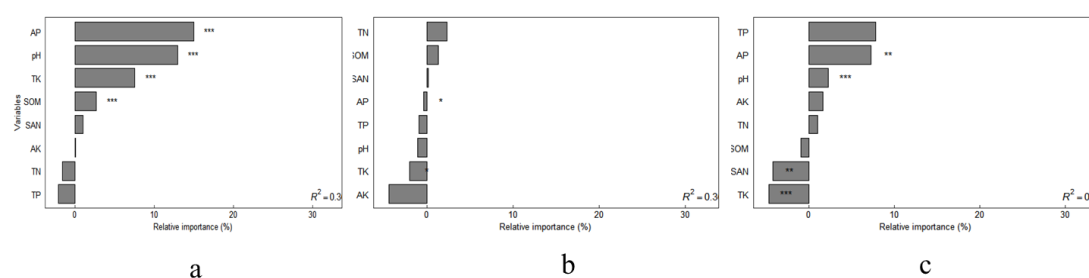


Figure 4. (a)DaFang' Random forests to distinguish the relative importance of soil nutrient characteristics and amino acid content. (b)BoZhou'. Random forests to distinguish the relative importance of soil nutrient characteristics and amino acid content. (c)QingZhen' Random forests to distinguish

the relative importance of soil nutrient characteristics and amino acid content. *indicates $p < 0.05$, while blank spaces represent non-significant correlations.

3.5. Analysis of the Impact of Soil Factors on reducing sugar content

Figure 5 illustrates the relative importance of various soil factors on the quality indicator of reducing sugars in pepper fruits. In Figure 5a, TN (total nitrogen) has the highest relative importance (close to 30%), indicating that total nitrogen has a significant impact on the reducing sugar content in pepper fruits in the Dafang region. Additionally, pH and SAN (available nitrogen) also have high importance. Similarly, in the Bozhou region, SAN (available nitrogen), AK (available potassium), and pH exhibit high importance, with a relatively balanced distribution of relative importance across variables, and several variables showing significance (Figure 5b). In the Qingzhen region, AK (available potassium) and pH show high relative importance, followed by SOM (soil organic matter) and TP (total phosphorus). However, with an R^2 of 0.28, the model's explanatory power is 28%, which is relatively low, suggesting that further analysis incorporating other environmental or soil factors may be necessary (Figure 5c). Overall, Figure 5 indicates that total nitrogen, available potassium, pH, and organic matter show high importance for reducing sugar content in all three regions.

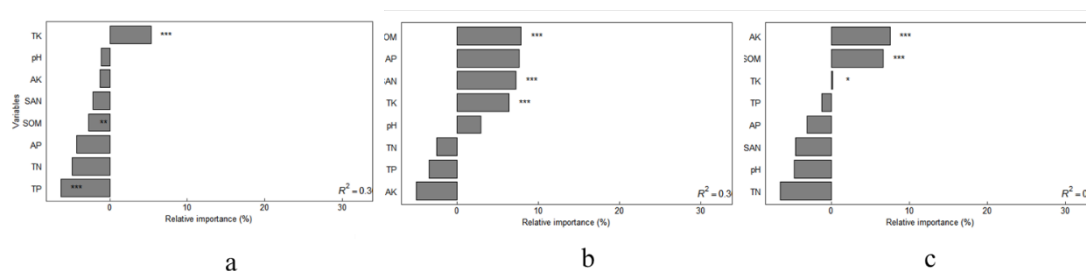


Figure 5. (a)DaFang' Random forests to distinguish the relative importance of soil nutrient characteristics and reducing sugars. (b)BoZhou'. Random forests to distinguish the relative importance of soil nutrient characteristics and reducing sugars. (c)QingZhen' Random forests to distinguish the relative importance of soil nutrient characteristics and reducing sugars. *indicates $p < 0.05$, while blank spaces represent non-significant correlations.

3.6. Analysis of the Impact of Soil Factors on reducing sugar content

Figure 6 represents the analysis results of the importance of different soil nutrients on capsaicin content across three regions, showing the relative importance of various soil nutrient factors on capsaicin (Relative importance %). In the Dafang region, AP (available phosphorus) has the highest relative importance in the model, about 30%, and shows significant importance (***). SOM (soil organic matter) and SAN (available nitrogen) also have relatively high importance (Figure 6a). In the Bozhou region, SAN (available nitrogen) holds the highest relative importance, with significant importance. This is followed by AK (available potassium), pH, and SOM (Figure 6b). In the Qingzhen region, AK (available potassium) has the highest relative importance and shows significant importance (***), followed by AP, SOM, and pH (Figure 6c). Overall, AP(available phosphorus), AK(available potassium), and AN(available nitrogen) show high importance across all three regions, indicating that these factors have a significant impact on capsaicin content.

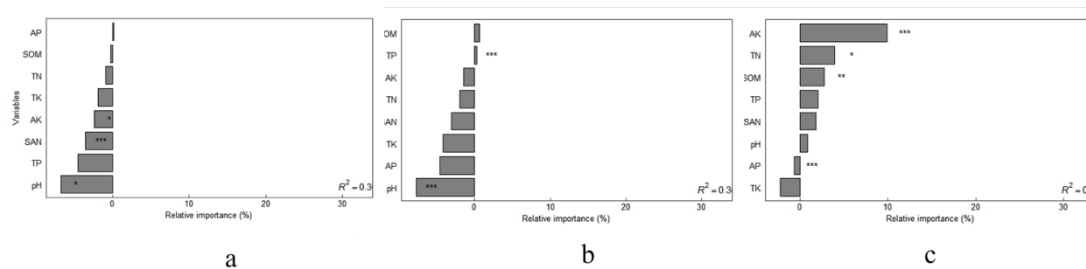


Figure 6. (a)DaFang' Random forests to distinguish the relative importance of soil nutrient characteristics and capsaisin. (b)BoZhou'. Random forests to distinguish the relative importance of soil nutrient characteristics and capsaisin. (c)QingZhen' Random forests to distinguish the relative importance of soil nutrient characteristics and capsaisin. *indicates $p < 0.05$, while blank spaces represent non-significant correlations.

3.7. Analysis of the Impact of Soil Factors on reducing sugar content

It presents the analysis results of the relative importance of multiple soil variables using a random forest model (Figure 7). In the Dafang region, AK (available potassium) holds a significant relative importance in this model (close to 70%), indicating that the AP(available potassium) content in Dafang has a highly significant impact on dihydrocapsaicin content. In addition, SOM (soil organic matter), SAN (available nitrogen), and AP (available phosphorus) also contribute to the model, but their significance is lower compared to AK (Figure 7a). In the Bozhou region, TN (total nitrogen) has a higher relative importance, suggesting that TN(total nitrogen) has a significant impact on dihydrocapsaicin content in this area. AK(available potassium), SAN(available nitrogen), and SOM (soil organic matter) also make certain contributions to the model (Figure 7b). In the Qingzhen region, AP (available phosphorus) and AK (available potassium) show high relative importance, marked with significance. TP (total phosphorus) and SOM (soil organic matter) also contribute to the model (Figure 7c). These figures reveal the relative importance of different soil nutrients on the dihydrocapsaicin content in pepper fruits, with available potassium (AK) showing high importance in multiple figures. This suggests that potassium has a generally significant impact on pepper fruit quality across different regions.

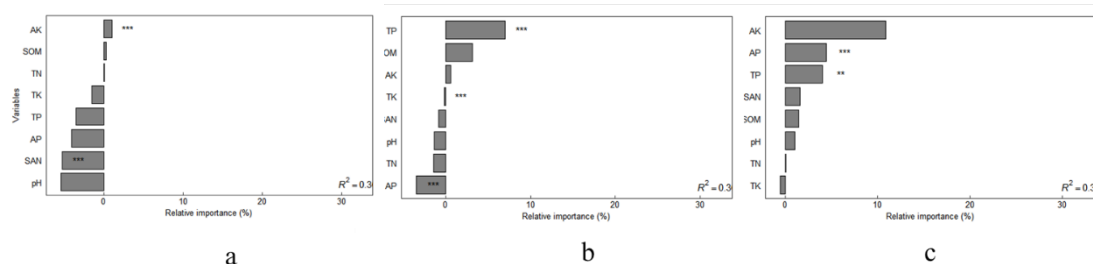


Figure 7. (a)DaFang' Random forests to distinguish the relative importance of soil nutrient characteristics and dihydrocapsaicin. (b)BoZhou'. Random forests to distinguish the relative importance of soil nutrient characteristics and dihydrocapsaicin. (c)QingZhen' Random forests to distinguish the relative importance of soil nutrient characteristics and dihydrocapsaicin. *indicates $p < 0.05$, while blank spaces represent non-significant correlations.

4. Discussion

The relationship between soil nutrients is complex, the content and interactions directly influence the absorption of nutrients, and then ultimately manifests in variations of fruit quality. The unique karst topography of Guizhou creates distinct ecological environments for pepper cultivation. This study revealed significant differences in soil nutrient content across the three pepper-growing regions of Dafang, Bozhou, and Qingzhen, leading to corresponding differences in pepper fruit quality.

Amino acids are key components contributing to vegetable quality and serve as precursors for flavor compounds[11], and they are greatly influenced by soil nutrients[12,13]. Shi's study[14] demonstrated that balanced fertilization with nitrogen, phosphorus, and potassium significantly enhances pepper quality indicators, including vitamin C content, free amino acid content, and total soluble sugars. Similarly, Chai's research[15] found that the application of ammonium polyphosphate increased amino acid content in pepper fruits. The results of this study showed that amino acid content across the three regions ranged from 23.06 to 60.96 $\mu\text{mol/g}$, with relatively high levels overall. However, the primary factors influencing amino acid content varied between regions. In Dafang, pH, AP (available phosphorus), and TK (available potassium) were the most influential factors, followed by SOM (soil organic matter). In Bozhou, TN (total nitrogen) and SOM were key, while in Qingzhen, TP (total phosphorus), AP, and pH were primary, with secondary influences from AK (available potassium), SOM, and SAN (available nitrogen). Overall, soil pH, available phosphorus, available potassium, and organic matter showed the most significant impact on amino acid levels in pepper fruit.

Sugars in pepper peppers, including reducing sugars, are primarily produced through photosynthesis and play vital roles as key components of cells, serving as signaling molecules and providing essential energy for growth and development. These sugars include soluble solids, reducing sugars (such as glucose, fructose, and maltose), and non-reducing sugars (such as sucrose)[16]. In this study, the reducing sugar content did not significantly differ across the three regions, ranging from 8.06 to 17.85 g/kg. However, the correlation between reducing sugars and soil nutrients varied between three regions. TN (Total nitrogen) plays a critical role in determining the reducing sugar content in Dafang region. In Bozhou, the primary influencing factors reducing sugar are SAN (available nitrogen), AK (available potassium), and pH, while in Qingzhen, AK (available potassium) and pH are the main factors, followed by SOM (soil organic matter) and TP (total phosphorus). So, TN (total nitrogen), AP (available phosphorus), pH, and SOM matter consistently show high importance for reducing sugars across all three regions. Analysis via correlation and random forest importance ranking shows regional variations in capsaicin determinants: AP (available phosphorus) has the highest influence in Dafang, followed by SOM (soil organic matter) and SAN (available nitrogen). In Bozhou, SAN dominates, with AP, SOM, and pH also significant. Collectively, available phosphorus, potassium, and nitrogen consistently exhibit the highest impact on capsaicin content. Chen Kun's findings [20] also reflect this trend, highlighting the effect hierarchy (phosphorus > potassium > nitrogen), consistent with our study. For dihydrocapsaicin, AK (available potassium) is most influential in Dafang, with SOM, SAN, and AP contributing. In Bozhou, TN (total nitrogen) is key, while AP and AK are predominant in Qingzhen. Summing up, AK (available potassium) has the greatest impact on dihydrocapsaicin. Chen et al. (2011) demonstrated that controlled potassium levels improve garlic's quality and nutritional profile, affirming potassium's pivotal role in enhancing capsaicin-related attributes in pepper fruit[16].

Capsaicinoids are the compounds responsible for the characteristic spiciness of pepper peppers, with capsaicin and dihydrocapsaicin being the most abundant. Together, they account for about 90% of total capsaicinoids and are key indicators of pepper quality[17]. Wan Kai's research[18] demonstrated that appropriate fertilization can significantly increase capsaicinoid content, thereby enhancing spiciness. Fu Wei's study[19] highlighted that the capsaicin levels in Guizhou's five main pepper varieties vary, with Wrinkled Pepper having the lowest content and Chaotianjiao (Upright Pepper) having the highest. In this study, capsaicin content in Dafang ranged from 0.38 to 3.28 g/kg, while in Bozhou, the content ranged from 0.12 to 3.49 g/kg, and in Qingzhen, it ranged from 0.48 to 6.39 g/kg. Correlation analysis revealed that dihydrocapsaicin content in Qingzhen was significantly positively correlated with available phosphorus and available potassium, consistent with the findings of Chen Kun[20], which indicated that the influence of fertilizers on capsaicin follows the order of phosphorus > potassium > nitrogen.

For dihydrocapsaicin, AK (available potassium) is the most impact factor in Dafang, with SOM, SAN, and AP contributing to a lesser degree. In Bozhou, TN (total nitrogen) is predominant, while AP and AK take precedence in Qingzhen. Overall, available potassium (AK) is the most influential for dihydrocapsaicin. Chen et al. (2011) further support this by showing that optimal potassium levels enhance both garlic quality and nutrient content, indicating potassium's crucial role in fruit quality and specific traits such as capsaicin and dihydrocapsaicin [21].

5. Conclusion

This research investigates the relationship between soil nutrient elements and the quality of pepper fruits, uncovering a significant correlation between soil nutrient composition and fruit quality. Studies have shown that nutrient imbalances in nitrogen, phosphorus, and potassium can negatively impact pepper quality, with both excesses and deficiencies leading to undesirable effects. Potassium, for instance, plays a critical role in fruit development, where insufficient potassium can lead to flower and fruit drop, ultimately lowering yield. Bao et al. (2006) identified a strong positive correlation between soil potassium content and both soluble solids and flavor quality in citrus fruits in Hubei, advocating for potassium fertilization to enhance specific nutrients, such as dihydrocapsaicin, in fruit [22]. Phosphorus is equally vital, supporting the growth of roots, branches, and buds and aiding in organic matter formation. This study's correlation analysis demonstrates that pH, total potassium, available nitrogen, available potassium, and available phosphorus are the soil nutrients most closely associated with key quality indicators (amino acids, reducing sugars, capsaicin, and dihydrocapsaicin) in peppers, with regional differences influencing specific impacts.

Analyzing the relationship between soil and pepper fruit quality allows for a deeper understanding of the interactions between soil nutrients and fruit quality. This provides valuable insights into explaining the harmonious flavor and spiciness of Guizhou pepper from a soil perspective.

While soil is an important factor affecting fruit quality, other factors such as pepper variety, climate, agricultural management practices, altitude, slope orientation, and yield also play significant roles. Although single-factor analysis can reveal the relationships between environmental factors and fruit quality, the ecological niches created by multiple environmental factors are often unique and irreplaceable, and they play a decisive role in determining the superior quality of Guizhou pepper. Guizhou's karst topography, complex terrain, and pronounced vertical climate differences, along with diverse climate types, create ecological environments that are particularly well-suited for pepper growth. Future research should therefore focus on the comprehensive effects of various factors on pepper quality to better assess the growth environment and elucidate the advantages of Guizhou pepper.

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