Effects of Nitrogen Fertilizer Application on Dragon Fruit Quality in Limestone Soil of Karst Regions: Postprint

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Date: 2023-12-24T00:00:00+00:00

Abstract

To investigate the effects of nitrogen fertilizer application levels on fruit quality of dragon fruit under limestone soil conditions in karst regions, a pot experiment simulating the soil environment of karst limestone areas was conducted using 'Taiwan Dahong' dragon fruit as the experimental material. Based on phosphorus (P) and potassium (K) applications of 0.216 and 0.324 kg, respectively, four nitrogen application levels were established (CK, T1, T2, T3). Twenty-one fruit quality indicators were measured to compare differences in dragon fruit quality among different nitrogen application levels, while comprehensive analysis of 11 appearance quality indicators was performed using principal component analysis. The results showed that: (1) Nitrogen application increased fruit soluble sugar content and soluble solids content, while decreasing protein content and dietary fiber content, with significant differences observed between the high nitrogen treatment (T3) and other treatments. With increasing nitrogen application, fruit titratable acid content and vitamin C content exhibited a trend of first increasing then decreasing, whereas the solid-acid ratio showed a trend of first decreasing then increasing. High nitrogen levels significantly increased fruit longitudinal and transverse diameters, fruit shape index, and single fruit weight. (2) Nitrogen application treatments decreased dragon fruit N content and increased P content, with significant differences in N and P contents among treatments. Fruit K content increased with increasing nitrogen application. Nitrogen application increased fruit B content and decreased fruit Cu content. The ranking of fruit Mn, Fe, Ca, and Mg contents among different treatments was T3 > T1 > CK > T2. Zn content exhibited a trend of first decreasing then increasing with nitrogen application. (3) The high nitrogen level treatment achieved the highest comprehensive evaluation score in principal component analysis, indicating that when planting dragon fruit in brown limestone soil of Guilin karst areas, supplemented with appropriate amounts of P and K

fertilizers, high nitrogen treatment is more conducive to improving dragon fruit quality, though adjustments should be made according to soil fertility conditions in actual production.

Full Text

Effects of Nitrogen Fertilizer Application on Pitaya Quality Grown in Calcareous Soil of Karst Areas

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Abstract: To investigate the effects of nitrogen fertilizer application levels on fruit quality of pitaya grown in calcareous soil of karst areas, a pot experiment was conducted to simulate the soil environment of karst regions. Using 'Taiwan Dahong' pitaya as experimental material and with phosphorus (P) and potassium (K) fixed at 0.216 kg and 0.324 kg respectively, four nitrogen application levels (CK, T1, T2, T3) were established. Twenty-one fruit quality indicators were measured to compare differences in pitaya quality under different nitrogen levels, while principal component analysis was used for comprehensive evaluation of 11 appearance quality indicators. The results showed: (1) Nitrogen application increased soluble sugar content and soluble solids content, while decreasing protein content and dietary fiber content, with significant differences between the high nitrogen treatment (T3) and other treatments. With increasing nitrogen application, titratable acid content and vitamin C content showed a trend of first increasing then decreasing, while the solid-acid ratio showed a trend of first decreasing then increasing. High nitrogen levels significantly increased fruit vertical and horizontal diameters, shape index, and single fruit weight. (2) Nitrogen application treatments decreased N content in pitaya fruit while increasing P content, with significant differences in N and P contents among treatments. Fruit K content increased with increasing nitrogen application. Nitrogen application increased fruit B content while decreasing Cu content. The ranking of Mn, Fe, Ca, and Mg contents among different treatments was T3 > T1 > CK > T2. Zn content showed a trend of first decreasing then increasing with nitrogen application. (3) The high nitrogen level treatment had the highest comprehensive evaluation score from principal component analysis, indicating that when selecting brown calcareous soil in Guilin karst areas for pitaya cultivation, supplemented with certain amounts of P and K fertilizer, high nitrogen treatment is more conducive to improving pitaya quality, though appropriate adjustments should be made according to soil fertility conditions in actual production.

Keywords: nitrogen fertilizer, karst calcareous soil, pitaya, fruit quality, mineral nutrition

Pitaya (*Hylocereus* spp.), a perennial climbing plant belonging to the Cactaceae family, originates from tropical desert regions of Central America and was later introduced to Southeast Asian countries such as Vietnam. In the early 1990s, it was introduced to Taiwan, China, and subsequently spread to Hainan, Fujian, Guangdong, Guangxi, and other regions. Pitaya fruit is rich in sugars, proteins, vitamins, dietary fiber, mineral elements, and other nutrients, offering high nutritional and health value as a widely popular fruit. In recent years, China's pitaya industry has developed rapidly, with planting area and total production exceeding Vietnam to rank first in the world, demonstrating strong development potential. Guangxi is the province with the largest pitaya planting area in China, leading the development of the country's pitaya industry (Lu et al., 2018a; Wang et al., 2020).

Guangxi is a major karst distribution area in China and one of the key regions for rocky desertification control. Conducting ecological restoration and ecological industry cultivation in karst rocky desertification areas is an effective measure for rocky desertification control. After more than twenty years of experimentation and promotion, pitaya has currently developed into an important agricultural pillar industry in the karst rocky mountainous areas of southwestern Guangxi, gaining widespread social recognition for its role in poverty alleviation and rocky desertification prevention (Lu et al., 2018b). Preliminary experimental demonstrations have shown that pitaya grows vigorously under the calcium-rich and alkaline environmental conditions of karst areas, demonstrating strong adaptability to karst environments. However, karst areas generally have shallow soil layers, limited total soil volume, and poor water and fertilizer retention capacity, requiring external addition of nitrogen and other nutrients to maintain pitaya productivity. To date, research on the fertilizer requirements of pitaya under karst calcareous soil conditions is extremely limited, with existing studies focusing primarily on acidic soils. Due to significant differences in physicochemical properties between calcareous and acidic soils, research results cannot directly guide pitaya cultivation in karst areas.

Nitrogen is an essential macronutrient for fruit tree growth and development, playing important roles in organ formation, substance metabolism, and physiological and biochemical processes. It primarily affects plant growth rate, morphological development, and the transport and distribution of tree nutrients (Duarte et al., 1993). Nitrogen application rate is one of the important factors determining plant growth and nutrient absorption and distribution. Appropriate nitrogen application can timely and adequately provide nutrients for fruit tree growth and development, continuously improve the physicochemical properties of rhizosphere soil, create favorable environmental conditions for robust tree growth, and increase yield and quality (Lao, 2001). Nitrogen deficiency can lead to poor branch development and insufficient storage nutrition, while excessive nitrogen not only reduces fruit quality in crops such as late navel orange (Brunetto et al., 2017), grapefruit (He et al., 2003), and mango (Nguyen et al., 2004), but also increases disease risk and environmental load, reducing the effective utilization rate of nitrogen by fruit trees (Qin et al., 2016). Alleyne et al. (1997) found in studying the effects of nitrogen application rate on blackberry quality that excessive nitrogen application had no adverse effects on fruit quality, possibly because different fruit tree varieties have different fertilizer requirements and tolerance to soil fertility.

Research has shown that pitaya has shallow root systems, strong continuous fruiting ability, high fertilizer demand, and is sensitive to soil nitrogen (Cheng et al., 2018). Pitaya has a relatively high nitrogen demand. Based on 85% water content in pitaya fruit, each harvest of 100 kg of fresh fruit removes 225 g of pure nitrogen (Li et al., 2021). Pitaya can naturally flower and fruit 12-15 batches annually with significant overlap, as bud germination, branch growth, and flowering/fruiting periods occur simultaneously, creating intense nutrient competition among organs (Liang et al., 2018). This may result in different nitrogen requirements compared to other fruit trees. Calcareous soil, as a typical karst soil in karst areas, is characterized by high calcium carbonate content, high pH values, poor water and fertilizer retention capacity, and easy loss of soil nutrients (such as organic matter and nitrogen) (Jiang et al., 2014), which can lead to high fertilizer input but insufficient fertilizer efficiency. Currently, pitaya growers in karst areas mostly rely on experience for fertilization, lacking reference nitrogen application rates, resulting in unstable yields, poor fruit quality, and poor commercial characteristics. Therefore, exploring economically efficient and environmentally friendly optimal nitrogen application rates has become key to the sustainable development of the pitaya industry in karst areas.

Therefore, this study used the main cultivated pitaya variety 'Taiwan Dahong' in Guangxi as experimental material, establishing a pot-controlled experiment with different nitrogen application levels under karst calcareous soil conditions. The study explored the effects of different nitrogen application rates on the nutritional components of pitaya cultivated in calcareous soil while verifying the application effects of common nitrogen application levels in pitaya production practice, aiming to provide scientific reference for rational fertilization of pitaya in karst calcareous soil.

1. Materials and Methods

1.1 Experimental Site Overview

The experiment was conducted at the Pitaya Cultivation Base of Guangxi Institute of Botany in Yanshan District, Guilin City (110°17 E, 25°01 N). The location has a mid-subtropical monsoon climate, with an altitude of approximately 180 m, annual rainfall of 1,900 mm, average annual sunshine of about 1,550 h, and average annual temperature of 19°C (Zhang et al., 2012).

1.2 Experimental Materials

Three-year-old 'Taiwan Dahong' pitaya seedlings with consistent growth, uniform fruiting branch numbers, no pests or diseases, and normal development were selected as experimental materials. The seedlings were approximately 120 cm tall and provided by Guangxi Institute of Botany. In February 2021, a specialized potting tool called "A Special Potting Rack for Pitaya" was designed. Plastic pots with a diameter of about 30 cm and height of about 35 cm were used as base pots, with a support stake placed in each pot. Three pitaya plants were planted in each pot (stake).

The experimental soil was brown calcareous soil collected from karst areas in Guilin, with basic physicochemical properties as follows: pH 7.56, organic matter 42.91 $g \cdot kg^{-1}$, total nitrogen 2.19 $g \cdot kg^{-1}$, total phosphorus 0.67 $g \cdot kg^{-1}$, total potassium 7.3 $g \cdot kg^{-1}$, available potassium 60.69 $mg \cdot kg^{-1}$, exchangeable calcium 26.55 mol(½ Ca^{2+}) $\cdot kg^{-1}$, and field water holding capacity 28.9%. According to the national second soil survey nutrient classification standards, this soil is alkaline with first-class organic matter content, first-class total nitrogen content, third-class total phosphorus content, fifth-class total potassium content, and fourth-class available potassium content. After collection, the soil was sieved to remove gravel and roots, then placed in plastic pots for later use, with each pot containing approximately 13.50 kg of soil.

Experimental fertilizers: Nitrogen fertilizer was urea ($N \geq 46\%$) produced by Xinjiang Tianyun Chemical Co., Ltd.; phosphorus fertilizer was calcium superphosphate ($P_2O_5 \geq 16\%$) produced by Hubei Kingenta Fertilizer Industry Co., Ltd.; potassium fertilizer was potassium sulfate ($K_2O \geq 50\%$) produced by Hubei Zhongnong Zhongjia International Trade Co., Ltd.

1.3 Experimental Design

According to Li et al. (2012), under alkaline soil conditions, the required N:P:K ratio for pitaya during the entire growth period is approximately 1:1:1.5. Based on application rates of N (24 kg), P (24 kg), and K (36 kg) per 667 m^2, each pot (stake) of pitaya received approximately 0.216 kg of pure nitrogen (3 plants/stake), 0.216 kg of pure phosphorus (3 plants/stake), and 0.324 kg of pure potassium (3 plants/stake).

This experiment established three different nitrogen levels with fixed phosphorus and potassium levels, totaling four treatments (CK, T1, T2, T3): CK was no nitrogen application, T1 was 0.108 kg, T2 was 0.216 kg, and T3 was 0.324 kg, with P and K at 0.216 kg and 0.324 kg respectively for all treatments. During fertilization, the amounts of pure nitrogen, phosphorus, and potassium were converted to the actual amounts of urea ($N \geq 46\%$), calcium superphosphate ($P_2O_5 \geq 16\%$), and potassium sulfate ($K_2O \geq 50\%$) per stake of pitaya. The urea ($N \geq 46\%$) application rates for CK, T1, T2, and T3 were 0, 0.352, 0.705, and 1.056 kg respectively, while phosphorus (16%) and potassium (50%) fertilizers were 1.350 kg and 0.648 kg respectively for all treatments.

A single-factor design was used, with each treatment planted with one pot of 'Taiwan Dahong' pitaya (3 plants/pot) and three replications, totaling 12 pots with 36 plants. Fertilization was applied twice annually, with 50% of the total nitrogen, phosphorus, and potassium applied as base fertilizer and 50% as top-dressing. The first fertilization was conducted in early March, and the second in mid-June. Circular trenches 5-10 cm deep and 5-8 cm wide were dug in the plastic pots, and fertilizers were evenly applied in the trenches according to the experimental treatments, mixed with soil, covered, and watered thoroughly once. All other management measures were identical except for the different nitrogen application rates.

1.4 Measurement Indicators and Methods

In August 2021 (peak fruiting period), mature pitaya fruits were collected. Three to five medium-sized, pest-free fruits were collected from each plant in fresh-keeping bags and brought back to the laboratory for processing. The following indicators were measured: vertical diameter, transverse diameter, shape index, single fruit weight, vitamin C (Vc), titratable acid, protein, dietary fiber, soluble sugar, soluble solids, N, P, K, Ca, Mg, Fe, B, Mn, Cu, and Zn. Measurement methods were as follows: single fruit weight was measured using an electronic balance (0.01 g precision); fruit vertical and transverse diameters were measured using a digital vernier caliper (0.01 mm precision); shape index was calculated as vertical diameter/transverse diameter; vitamin C content was determined by 2,6-dichloroindophenol titration (GB5009.86-2016); titratable acid content by titration (GB/T 12456-2008); dietary fiber content by enzymatic-gravimetric method (GB 5009.88-2014); soluble sugar content by 3,5-dinitrosalicylic acid colorimetry (NY/T 2742-2015); soluble solids content by refractometry (GB/T12295) measured at the fruit center. Nitrogen and protein contents were determined by the Kjeldahl method; phosphorus content by molybdenum-antimony colorimetry; potassium content by atomic absorption spectrophotometry; Ca, Mg, Fe, B, Mn, Cu, and Zn contents by nitric acid-hydrofluoric acid-perchloric acid digestion followed by inductively coupled plasma mass spectrometry (GB 5009.268-2016).

1.5 Data Analysis

Excel was used for data statistics, and SPSS 22.0 was used for one-way ANOVA and principal component analysis.

2. Results

2.1 Effects of Nitrogen Application Levels on Pitaya Quality Indicators

As shown in Table 1 , under the T2 treatment, fruit vertical diameter, transverse diameter, shape index, and single fruit weight were the lowest. Except for shape index, other indicators under T2 treatment were significantly lower than other treatments (P < 0.05). Single fruit weight under T3 treatment was significantly higher than other treatments (P < 0.05). There were no significant differences in shape index among treatments (P > 0.05).

As shown in Table 2 , under T3 treatment, soluble solids, soluble sugar, and solid-acid ratio were the highest, while titratable acid, vitamin, protein, and dietary fiber contents were the lowest. Soluble solids and soluble sugar contents showed an increasing trend with increasing nitrogen application, with T3's soluble solids content significantly higher than other treatments (P < 0.05). The solid-acid ratio showed a trend of first decreasing then increasing with nitrogen application, with T3 significantly higher than other treatments (P < 0.05). Vitamin C content and titratable acid content showed a trend of first increasing then decreasing with nitrogen application, with significant differences in titratable acid content among treatments (P < 0.05). Vitamin C content under T1 treatment was significantly different from other treatments. Compared with CK, nitrogen application treatments showed a decreasing trend in protein content, with significant differences among T1, T2, and T3. Dietary fiber content showed a decreasing trend with increasing nitrogen application, with CK and T1 significantly higher than other nitrogen treatments (P < 0.05).

Table 1 Effect of nitrogen fertilizer application on fruit characters of pitaya

Treatment	Vertical diameter	Transverse diameter	Shape index	Single fruit weight
	79.24ab	75.28b	1.34a	321.90bc
	106.16a	100.65ab	1.34a	352.47b
	67.34bc	89.46bc	1.33a	293.80d
	82.09a	119.95a	1.46a	384.85a

Note: Different letters in each column indicate significant differences between different treatments (P < 0.05). The same below.

Table 2 Effect of nitrogen fertilizer application on fruit quality of pitaya

Treatment	Total soluble solids	Soluble sugar	Titratable acid	Solid acid ratio	Vitamin C	Protein	Dietary fiber
	18.2b	9.17c	1.52b	12.6a	18.41a	11.95b	29.42a
	18.48b	10.3b	1.98a	10.3c	18.35a	9.33b	13.09b
	18.88b	13.6a	1.44c	10.9b	15.59b	12.71c	
	21.43a	13.8a	0.73d	18.41a	12.71c		

2.2 Effects of Different Nitrogen Treatments on Macro- and Micro-Element Contents in Pitaya

As shown in Figure 1 [Figure 1: see original paper], under CK treatment, N content was the highest at 2.02 $g \cdot kg^{-1}$; under T3 treatment, P, K, Ca, and Mg contents were the highest at 0.39, 2.51, 0.083, and 0.29 $g \cdot kg^{-1}$ respectively. Compared with CK, N content in other treatments decreased by 13.9%-25.7%, while P and K contents increased by 11.9%-53.2% and 3.3%-10.8% respectively. Ca content in T2 decreased by 1.4% compared with CK, while Ca contents in T1 and T3 increased by 6.7% and 8.6% respectively. Mg content in T2 decreased by 13.9% compared with CK, while Mg contents in T1 and T3 increased by 6.7% and 7.2% respectively. ANOVA results showed that compared with CK, other treatments decreased pitaya fruit N content and increased P content, with significant differences in N and P contents among treatments ($P < 0.05$). Fruit K content increased with increasing nitrogen level, with T3 treatment significantly higher than other treatments ($P < 0.05$). Ca contents in T1 and T3 treatments were significantly higher than CK ($P < 0.05$), while Mg content in T2 was significantly lower than other treatments ($P < 0.05$).

As shown in Figure 2 [Figure 2: see original paper], under CK treatment, Cu content was the highest at 0.59 $mg \cdot kg^{-1}$; under T3 treatment, Mn, Fe, and Zn contents were the highest at 0.91, 3.29, and 2.83 $mg \cdot kg^{-1}$ respectively; under T2 treatment, B content was the highest at 3.70 $mg \cdot kg^{-1}$. Compared with CK, B content increased under the other three treatments, while Cu content showed the opposite trend. Mn, Fe, Cu, and Zn contents were the lowest under T2 treatment. ANOVA results showed that compared with CK, B content in pitaya fruit was increased under T1, T2, and T3 treatments, with T2 significantly different from other treatments ($P < 0.05$). T1, T2, and T3 significantly decreased pitaya fruit Cu content, with significant differences among treatments ($P < 0.05$). Among nitrogen treatments, the ranking of fruit Mn, Fe, Cu, and Zn contents was T3 > T1 > T2, with T2 significantly lower than other treatments ($P < 0.05$).

Different lowercase letters indicate significant differences between different treatments ($P < 0.05$). The same below.

Figure 1 Macroelement contents of pitaya in different treatments [Figure 1: see original paper]

Figure 2 Trace element contents of pitaya in different treatments [Figure 2: see original paper]

2.3 Principal Component Analysis and Comprehensive Evaluation of Pitaya Fruit Quality

Fruit quality decisively affects its popularity among consumers. Both fruit appearance and edible quality determine comprehensive fruit quality, with external factors such as size and shape determining external sensory quality, and edible factors such as sugars and organic acids determining nutritional value. This study used SPSS 22.0 to conduct principal component analysis on 11 quality indicators of pitaya. As shown in Table 3 , three principal components were extracted with eigenvalues greater than 1.000, with a cumulative variance contribution rate of 87.48%, containing the vast majority of original data information. Therefore, the first three principal components should be used as analysis indicators for pitaya quality evaluation. The variance contribution rate of the first principal component was 55.42%, with the largest contribution from shape index, followed by protein, transverse diameter, vitamin C, soluble solids, and soluble sugar. The variance contribution rate of the second principal component was 18.56%, with high load values on single fruit weight, dietary fiber, and soluble solids. The variance contribution rate of the third principal component was 13.49%, with high load values on solid-acid ratio, vertical diameter, and titratable acid.

Based on the factor score coefficient matrix in Table 4 and its corresponding principal components, each principal component factor score can be calculated. The score expressions are as follows:

F_1 = -0.151X_1 - 0.104X_2 + 0.160X_3 + 0.086X_4 + 0.121X_5 + 0.115X_6 + 0.078X_7 + 0.139X_8 + 0.109X_9 - 0.153X_{10} - 0.094X_{11}

F_2 = 0.178X_1 + 0.120X_2 - 0.003X_3 + 0.396X_4 + 0.302X_5 + 0.098X_6 + 0.228X_7 - 0.054X_8 - 0.353X_9 + 0.053X_{10} + 0.061X_{11}

F_3 = -0.008X_1 - 0.484X_2 - 0.001X_3 - 0.020X_4 - 0.047X_5 - 0.070X_6 + 0.348X_7 + 0.036X_8 + 0.085X_9 + 0.188X_{10} + 0.517X_{11}

Where: X_1 to X_{11} represent 11 quality indicators including fruit transverse diameter, vertical diameter, shape index, single fruit weight, soluble solids, soluble sugar, titratable acid, vitamin C, dietary fiber, protein, and solid-acid ratio; F_1 to F_3 represent scores for each principal component.

Combining the principal component factor score formulas and using principal component variance contribution rates as weights, a comprehensive evaluation score (F) function for pitaya quality was constructed as follows: F = 0.55F_1 + 0.19F_2 + 0.13F_3.

Based on the comprehensive evaluation score function, comprehensive scores and rankings for pitaya quality under different treatments can be calculated, with higher comprehensive scores indicating better comprehensive quality. As shown in Table 5 , T3 treatment had the highest ranking, indicating that T3 treatment had relatively better comprehensive quality.

Table 3 Principal component load matrix, eigenvalue and variance contribution rate of the quality index of pitaya [Table content with Quality index, Principal component load values, Eigenvalues, Variance contribution, and Cumulative contribution rates]

Table 4 Matrix of factor score coefficient [Table content with Quality index and Score coefficient of each component factor]

Table 5 Factor score and comprehensive score [Table content with Treatment, F1, F2, F3, Comprehensive score, and rank]

3. Discussion

3.1 Yield Effects of Nitrogen Application on Pitaya in Calcareous Soil

Nitrogen is not only an important material basis for plant growth and development but also a key factor affecting fruit appearance quality and nutritional quality. Rational nitrogen application is an important approach to improving plant fruit quality (Tan et al., 2021). Pitaya produces multiple batches of fruit, and the correlation between fertilizer application amount and quality indicators varies among batches (Chen et al., 2019). Single fruit weight and fruit diameter reflect fruit size and are important external quality indicators affecting fruit appearance and commercial grade. In this study, yield indicators of mature pitaya fruits grown in calcareous soil showed that different nitrogen application levels had no significant effect on pitaya shape index, but when nitrogen application increased to a certain amount, vertical and horizontal diameters increased accordingly, thereby increasing single fruit weight. Under the calcium-rich and alkaline environmental conditions of karst areas, the nitrogen supply capacity of calcareous soil is relatively low. Nitrogen participates in the synthesis of compounds such as proteins, nucleic acids, and chlorophyll in plants, promoting plant growth and development and improving crop productivity. This indicates that nitrogen is an important fertility factor for high pitaya yield in both acidic and calcareous soils. Appropriate nitrogen application can promote pitaya vegetative growth, flower bud differentiation, photosynthesis, and has positive significance for yield formation.

3.2 Quality Effects of Nitrogen Application on Pitaya in Calcareous Soil

Pitaya fruit is rich in nutritional components and functional substances. Wang et al. (2020) identified soluble sugar, protein, and titratable acid as important indicators for evaluating pitaya quality. The solid-acid ratio, as a comprehensive indicator measuring sugar and acid content, is a key factor affecting fruit flavor. Higher ratios indicate more suitable flavor and taste, directly affecting commercial value (Wang et al., 2020). Rational nitrogen application can promote fruit growth and development, significantly increase soluble solids and vitamin C content, and reduce titratable acid content (Zhang et al., 2017). Nitrogen supply directly affects the synthesis of photosynthetic products and amino acids in plants. Plants can synthesize sucrose through photosynthesis and sugar metabolism, increasing sugar content in fruits (Xu et al., 2022). Additionally, sucrose metabolism enzyme activity stimulated by nitrogen levels can increase soluble sugar content (Liu et al., 2015). This study showed that for 'Taiwan Dahong' pitaya grown in calcareous soil, both soluble sugar and soluble solids contents increased with increasing nitrogen application, while titratable acid content decreased with increasing nitrogen application. Under T3 treatment, soluble solids content, soluble sugar content, and solid-acid ratio all increased compared with CK, while titratable acid content decreased, consistent with the research results of Li et al. (2010). Soluble solids content also increased with nitrogen application across treatments, possibly because soluble solids are mainly composed of soluble sugars (Yuan et al., 2009). Hu et al. (2023) found that nitrogen fertilizer application can significantly increase soluble sugar content in grape fruits, reduce total acidity, and promote the solid-acid ratio. In this study, except for low nitrogen levels, the solid-acid ratio generally increased with nitrogen application level, indicating that appropriate nitrogen application can regulate fruit solid-acid ratio and improve flavor quality. In this study, vitamin C contents under T1 and T2 treatments were higher than CK, while T3 treatment was lower than CK, showing a trend of first increasing then decreasing with increasing nitrogen supply, similar to the findings of Yang et al. (2007) that increasing nitrogen fertilizer can improve fruit tree vitamin C content, but excessive fertilizer is not conducive to vitamin C accumulation. The possible reason is that nitrate accumulation in plant fruits is positively correlated with nitrogen application rate. When nitrogen application is high, the reaction between vitamin C and nitrite directly leads to vitamin C loss (Duan et al., 2016). In this study, dietary fiber content decreased with increasing nitrogen application, possibly because dietary fiber is mainly composed of lignin, polysaccharides, and nitrogen-containing substances. Combined nitrogen application promoted plant nitrogen absorption and transport to fruits, correspondingly reducing the accumulation of ineffective carbohydrates (dietary fiber) in fruits (Xu et al., 1997).

3.3 Mineral Element Responses in Pitaya Fruit to Nitrogen Application in Calcareous Soil

The levels and ratios of nitrogen, phosphorus, and potassium in fruits affect fruit quality. Nitrogen affects fruit color, maturity, and protein content; phosphorus content can regulate starch, sugar, and various vitamin contents in fruits; potassium can improve fruit quality and enhance disease and pest resistance. Nitrogen fertilizer application can significantly increase the absorption and accumulation of N, P, and K elements in fruits (Chai et al., 2011). Li et al. (2012) showed that N, P, and K contents in pitaya fruit are closely related to nitrogen, phosphorus, and potassium application rates. In this study, under nitrogen application treatments, fruit P and K contents were higher than CK, similar to the above research. However, fruit N content and protein content under nitrogen treatments were lower than CK, possibly because the alkaline characteristics of calcareous soil are prone to ammonia volatilization, causing certain nitrogen losses (Li et al., 2017). It may also be related to dry matter accumulation distribution and nutrient absorption patterns. Excessive nitrogen application can cause nitrogen assimilation products to transfer and accumulate in plant vegetative organs, reducing distribution to reproductive organs and affecting fruit N content accumulation, thereby affecting protein content (Wang et al., 2023). Nitrogen fertilizer application has obvious promoting effects on the absorption of medium and trace elements in fruit tree root systems, subsequently affecting trace element contents in fruits (Ma et al., 2018). Additionally, certain synergistic or antagonistic relationships exist among mineral elements. Li et al. (2022) found that under consistent phosphorus and potassium application, nitrogen fertilizer application significantly increased passion fruit Ca content but significantly decreased Mg, Cu, Fe, and Zn contents. Phosphorus content in tomato fruits was significantly positively correlated with Mg, Fe, and Zn contents, and Mg content was significantly positively correlated with Fe and Zn contents (Jin et al., 2020). This study showed that under calcareous soil cultivation conditions, with fixed phosphorus and potassium fertilizer, Ca and Mg contents were highest under high nitrogen treatment, B content under nitrogen treatments was higher than the control with the highest content at medium nitrogen level, and Mn, Fe, Cu, and Zn contents were lowest at medium nitrogen level and gradually increased to the highest value at high nitrogen level. Calcium deficiency in fruits can easily lead to physiological diseases in plants. Magnesium is an important component of plant chlorophyll. Manganese directly participates in the oxygen evolution process of photosynthesis. Iron affects the redox system and photophosphorylation process. Copper participates in nitrogen metabolism in plants. Zinc promotes carbon dioxide fixation in photosynthesis (Lu, 1994). Pitaya quality formation depends on organic substances produced by photosynthesis. T3 treatment had the highest contents of Ca, Mg, Mn, Fe, Cu, and Zn in fruits, indicating that T3 treatment with higher nitrogen application can promote the transport of mineral elements required for pitaya photosynthesis, thereby increasing mineral content in fruits. This is similar to the findings of Lian et al. (2020) that tomato fruit Ca and Mg contents were higher under high nitrogen treatment, followed by Zn, Fe, Mn, and Cu. Fruit B content showed a significant negative correlation with Mn, Fe, Cu, and Zn contents, indicating that under this study's conditions, most mineral elements showed synergistic effects, while a few showed antagonistic effects, and there were interactive effects in pitaya fruit mineral element absorption and accumulation.

Principal component analysis can simplify many originally correlated indicators into a few representative indicators that are relatively independent or have low correlation, retaining the vast majority of original information. This approach is faster and more accurate than single evaluation and avoids the influence of correlations among traits on evaluation results (Ye et al., 2022). This experiment's results showed that T3 treatment had the highest comprehensive score.

In summary, although this study clarified the effects of nitrogen fertilizer application on pitaya fruit quality grown in calcareous soil, the nitrogen release characteristics and its long-term slow-release mechanism after input are not yet clear. More long-term and systematic positioning monitoring is needed for demonstration to fully understand the changing patterns of soil nutrients, tree nutrients, and fruit quality in pitaya orchards.

Under calcareous soil cultivation conditions, different nitrogen application rates significantly affected pitaya quality indicators and mineral element contents. Nitrogen application increased fruit soluble sugar and soluble solids contents, decreased protein and dietary fiber contents. Fruit titratable acid and vitamin C contents showed a trend of first increasing then decreasing with nitrogen application, while the solid-acid ratio showed the opposite trend. High nitrogen levels increased fruit vertical and horizontal diameters, shape index, and single fruit weight. Regarding pitaya mineral elements, nitrogen application increased fruit P, K, Ca, and B contents, decreased N, Zn, and Cu contents, and high nitrogen levels promoted the accumulation of Mg, Mn, and Fe contents. Principal component analysis effectively reduced the dimensionality of measured indicators and provided comprehensive scoring, with results consistent with fruit quality, indicating that the comprehensive scoring had good representativeness. T3 treatment had the highest comprehensive evaluation score, indicating that this treatment could improve pitaya quality and increase its commercial value and economic benefits. The conclusions of this study were based on calcareous soil in the suburbs of Guilin. Due to differences in soil fertility backgrounds in different karst areas, appropriate fertilization and management measures should be formulated according to the soil physicochemical properties and management objectives of local plantations.

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Note: Figure translations are in progress. See original paper for figures.