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# Increasing Calcium and Decreasing Nitrogen Fertilizers Improves Peanut Growth and Productivity by Enhancing Photosynthetic Efficiency and Nutrient Accumulation in Acidic Red Soil

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**Abstract:** Excessive nitrogen and insufficient calcium could significantly impact peanut yields. This study investigated the effects of nitrogen and calcium fertilizers on nutrient absorption, utilization, and yield; experiments were conducted using the peanut cultivar from Xianghua 2008 in a split-plot arrangement with two calcium fertilizer levels ($Ca_0$: 0 and $Ca_1$: 568 kg CaO ha$^{-1}$) in the main plots and six nitrogen fertilizer gradients ($N_0$: 0, $N_{45.0}$: 45.0, $N_{90.0}$: 90.0, $N_{112.5}$: 112.5, $N_{135.0}$: 135.0, and $N_{157.5}$: 157.5 kg N ha$^{-1}$) in subplots between 2015 and 2016 in Changsha, China. We examined the impact of different rates of calcium and nitrogen fertilizers on the net photosynthetic rate (*Pn*), agronomic traits, dry matter quality, yield and yield composition, nutrient accumulation, and distribution. The combined application of calcium and nitrogen fertilizers significantly affected the yield and yield components, *Pn*, main stem height, dry matter, and nutrient accumulation. Under the same calcium level, nitrogen application significantly increased the main stem height and *Pn* and promoted the accumulation of dry matter and nutrients in the plant, particularly in the kernel. Under the same nitrogen treatment, calcium significantly increased *Pn* and promoted the accumulation of dry matter, calcium, and magnesium. The pod yield increased gradually with an increasing nitrogen application rate (0–112.5 kg ha$^{-1}$) and peaked at $N_{112.5}$, increasing by 52.3–138.0% compared with $N_0$. However, excessive nitrogen application (N > 112.5 kg ha$^{-1}$) decreased the pod yield. Under different nitrogen fertilizer levels, calcium application increased pod yields by 11.5–29.6% by promoting *Pn*, nutrient uptake, accumulation in the individual plant, and nutrient accumulation in the kernel. Therefore, this study suggested that adjusting the calcium (568 kg ha$^{-1}$) and nitrogen (112.5 kg ha$^{-1}$) fertilizer rates significantly improved peanut growth and productivity by enhancing photosynthetic efficiency and nutrient accumulation in calcium-deficient acidic red soil.

**Keywords:** *Arachis hypogaea* L.; red soil; nitrogen; calcium; productivity; photosynthetic efficiency; nutrient accumulation

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**Citation:** Wang, J.; Geng, Y.; Zhang, J.; Li, L.; Guo, F.; Yang, S.; Zou, J.; Wan, S. Increasing Calcium and Decreasing Nitrogen Fertilizers Improves Peanut Growth and Productivity by Enhancing Photosynthetic Efficiency and Nutrient Accumulation in Acidic Red Soil. *Agronomy* **2023**, *13*, 1924. https://doi.org/10.3390/agronomy13071924

Academic Editor: Andrea Baglieri

Received: 21 June 2023
Revised: 11 July 2023
Accepted: 18 July 2023
Published: 20 July 2023



## 1. Introduction

*Arachis hypogaea* L. is an important crop; it holds a significant role in the global economy and is crucial to food and oil security. The peanut is a major economic crop in the red soil region, which constitutes 22.7% of China's national land area [1]. However, the inherent characteristics of red soil, such as acidity, low phosphorus and calcium, and low organic matter, pose significant challenges to peanut cultivation [2]. Severe soil acidification results in the loss of cations, such as calcium and magnesium, owing to soil erosion. Additionally, excessive use of fertilizer in peanut cultivation can reduce the efficiency of fertilizers, cause ecological pollution, and degrade soil quality, ultimately leading to a decline in the sustainable production capacity [3–5]. Therefore, addressing the issues in the red soil region and using appropriate fertilization strategies are vital to promote peanut growth and development, nutrient accumulation and distribution, and increasing yield.

Nitrogen is an essential nutrient element for plant growth, with a significant impact on plant physiology, yield, and quality [6]. Peanuts have a high demand for nitrogen fertilizer; proper nitrogen management is a key agronomic factor for improving peanut yields. In previous studies, a lack of nitrogen slowed plant growth and development, decreased leaf area and photosynthesis, accelerated plant senescence, caused the degradation of nitrogen components, and ultimately reduced plant production [7,8]. Nitrogen fertilizer application improved peanut growth and promoted biomass production. It directly influenced the amino acid composition of proteins, which in turn influenced the nutritional quality [9]. In recent years, studies on nitrogen fertilization in red soil areas have increased worldwide; the focus has been on crop growth, nutrient accumulation and absorption, and yield [10–12]. Previous study has demonstrated that nitrogen fertilization applied 10 weeks after planting had minimal effects on the shoot and root–rhizome biomass [13]. Liu, Gao, Li, et al. [14] reported that the peanut pod yield increased within a certain range of nitrogen application; the yield no longer increased or even declined beyond the optimal nitrogen application rate [15]. Therefore, the impacts of nitrogen supply and utilization vary under different ecological environments. However, the effects of different nitrogen application rates on peanut growth, nutrient utilization, and yield in the red soil region of southern China require further investigation.

Calcium is also an essential nutrient element for peanut growth; it holds a crucial role in the maintenance of normal growth and metabolism [16]. Calcium acts as a ubiquitous second messenger that regulates plant growth and development in response to various biotic and abiotic stresses [17,18]. In addition, calcium is also an important component of cell walls and membranes, helping to maintain the normal structure and function of cells and reduce or delay damage to cell membranes [19]. However, calcium deficiency can depress plant growth, damage cell membranes, and impair chlorophyll biosynthesis [20], leading to soil acidification and the formation of insoluble salt precipitates between calcium ions and other elements [21], ultimately affecting peanut growth and yield. A previous study reported that peanut yields were lower when the calcium content in red soil was 148 mg kg$^{-1}$ and no external calcium was applied; however, calcium fertilizer significantly increased the calcium accumulation in peanut seeds and achieved a synergistic absorption of calcium, nitrogen, phosphorus, and potassium [22]. Calcium oxide (CaO) is a suitable calcium fertilizer for red soil regions; it has been reported to be beneficial when applied at a rate of 600 kg ha$^{-1}$ [22,23]. Calcium fertilizer in red soil areas not only promoted chlorophyll content but also significantly increased pod yields [24]. Moreover, compared with traditional fertilization, the reduction of nitrogen fertilizer and the addition of calcium fertilizer significantly increased the number and fresh weight of root nodules in the podding period, improved the relative content of chlorophyll and the accumulation of dry matter in the later fertility period, promoted the activities of carbon and nitrogen in leaves, and increased the yield by 4.5% [25]. In the case of nitrogen and calcium interactions, the net photosynthetic rate, leaf area index, and yield were the highest when a 25% nitrogen reduction was combined with a treatment of 300 kg ha$^{-1}$ calcium fertilizer [26]. However, studies on the interaction between nitrogen and calcium fertilizers in red soil areas to promote plant growth, nutrient uptake, and utilization and improve peanut yield are limited.

The current study hypothesizes that modifying the ratios of nitrogen and calcium fertilizers can affect peanut growth and productivity by altering the photosynthetic efficiency and nutrient accumulation in acidic red soil. The objective is to explore the optimal ratio of nitrogen and calcium fertilizers to increase peanut yields in the red soil region. To achieve this, we will investigate the effects of nitrogen and calcium fertilization on various parameters, such as the leaf photosynthetic rate, agronomic traits, dry matter accumulation, nutrient uptake and distribution, and peanut yield. The results of this study will provide technical guidance for high-yield, efficient peanut production and offer a theoretical framework for sustainable agricultural production.

## 2. Materials and Methods

### 2.1. Experimental Site and Field Conditions

A 2-year field experiment from 2015 to 2016 was conducted in the Yunyuan Experimental Station, Hunan Agricultural University (27°91′ N, 111°52′ E), Changsha, China, which is in the middle reaches of the Yangtze River with a subtropical, moist monsoon climate. The quaternary red topsoil of Shuyuan Village in the experimental field is typical calcium-deficient red soil. The physical and chemical properties of the soil in this study are shown in Table 1.

**Table 1.** The physical and chemical properties of the soil in this study in 2015 and 2016.

| Year | Organic Matter Content ($g\ kg^{-1}$) | Total Nitrogen Content ($g\ kg^{-1}$) | Total Phosphorus Content ($g\ kg^{-1}$) | Total Potassium Content ($g\ kg^{-1}$) | Alkaline Nitrogen Content ($mg\ kg^{-1}$) | Available Phosphorus Content ($mg\ kg^{-1}$) | Available Potassium Content ($mg\ kg^{-1}$) | Exchangeable Calcium Content ($mg\ kg^{-1}$) | Exchangeable Magnesium Content ($mg\ kg^{-1}$) | pH |
|---|---|---|---|---|---|---|---|---|---|---|
| 2015 | 7.30 | 0.82 | 0.33 | 17.00 | 64.00 | 0.90 | 82.00 | 148.00 | 0.26 | 4.50 |
| 2016 | 9.02 | 0.52 | 0.45 | 13.34 | 81.31 | 1.62 | 69.03 | 204.00 | 0.23 | 4.50 |

The basic meteorological data from the growth period of summer 2015 and spring 2016 are presented in Figure 1. The mean daily temperature was 22.2 and 26.6 °C and the rainfall was 487.4 and 681.0 mm in 2015 and 2016, respectively.

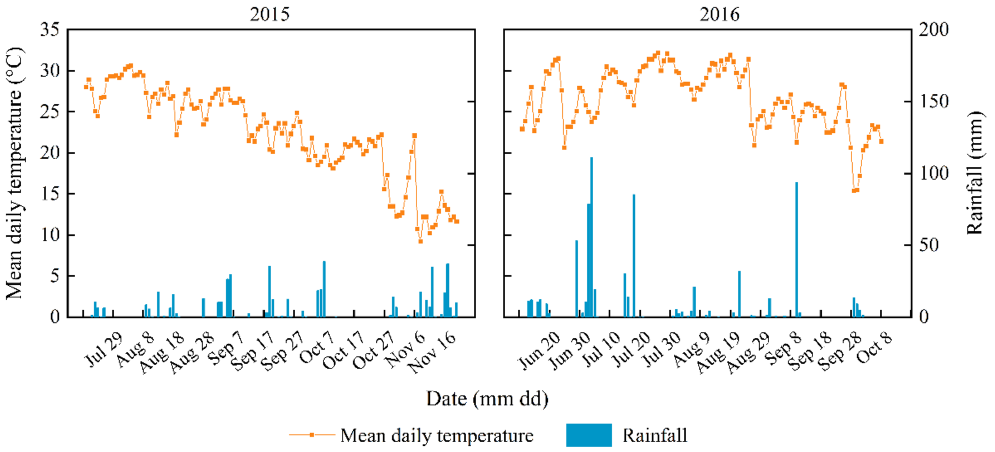


**Figure 1.** Changes of mean daily temperature and rainfall in peanut growing season in 2015 and 2016.

### 2.2. Experimental Materials and Design

The experiment was designed in a split-plot arrangement with two calcium (Ca) fertilizer levels ($Ca_0$: 0 and $Ca_1$: 568 kg CaO $ha^{-1}$) in the main plots and six nitrogen (N) fertilizer gradients ($N_0$: 0, $N_{45.0}$: 45.0, $N_{90.0}$: 90.0, $N_{112.5}$: 112.5, $N_{135.0}$: 135.0, and $N_{157.5}$: 157.5 kg N $ha^{-1}$) in the subplots with 8 replications. The fertilizer level 568 kg CaO $ha^{-1}$ was selected from previous experiments and was consistent with the use of calcium fertilizer in the published literature [27]; namely, calcium hydroxide $Ca(OH)_2$ was 750 kg $ha^{-1}$, and the equivalent to calcium oxide was 568 kg $ha^{-1}$. The peanut seeds of Xianghua 2008 were sown on 20 July 2015 and 11 June 2016 using the soil column cultivation method. The fertilizer, potassium dihydrogen phosphate, was applied at a rate of 325.0 kg $ha^{-1}$ in each experimental plot at pre-planting. Other field and plant management practices were adopted according to local peanut production practices, according to Li and Liu [28].

The soil columns used PVC pipes (37.5 cm inner diameter, 70 cm height) containing 100 kg of dry soil with four seedlings. Before being filled with soil, the PVC pipes were horizontally cut into two parts with a chainsaw for the convenience of layered sampling of the root system; the gap was sealed with tape to ensure that the side of the pipes did not leak water or fertilizer. The bottoms of the pipes were sealed with a double-layer plastic film at a height of 10 cm; the bottoms and tops of the pipes were tied tightly with iron wire. Afterwards, the bottoms of the pipes were buried at the solid and smooth soil ridge

(100 cm width, 10 cm height); a double-layer plastic film further isolated the root system from outside of the pipes. Two rows of pipes were arranged on each ridge.

### 2.3. Analysis of Net Photosynthetic Rate

The net photosynthetic rate (*Pn*) of six functional peanut leaves in each treatment was measured using a portable photosynthesis system (Li-6400, Li-COR, Lincoln, NE, USA) from 9:30–11:30 am, 50 days after sowing in 2015 and 2016. A fluorometer leaf chamber (6400-40) measured *Pn* according to the following settings: 380 ± 5 μmol $mol^{-1}$ $CO_2$ concentration, 1000 μmol $m^{-2}$ $s^{-1}$ photosynthetic photon flux density (red and blue light sources), and 65 ± 5% relative air humidity.

### 2.4. Determining the Nutrient Contents in Each Organ

The nutrient contents, including nitrogen, phosphorus, potassium, calcium, and magnesium, were determined by the $H_2SO_4$–$H_2O_2$ extraction method. The samples were weighed and placed in a glass tube before being crushed by a high-speed universal crusher (passing 80 mesh screens) and heated at 350 °C. $H_2SO_4$ was added, followed by $H_2O_2$ in addition to pure water. Lastly, the solution was filtered, and the filtrate was stored for further analysis.

The nitrogen and phosphorus contents were determined by a San$^{++}$ continuous flow analyzer (Skalar, Breda, The Netherlands) according to Wang et al. [23] and Soong et al. [29]. The potassium, calcium, and magnesium contents were measured with an inductively coupled plasma-based emission spectrometer (ICPE-9000, Perkin Elmer, Waltham, MA, USA), as described by Wang et al. [23]. The accumulation ($A_{organ}$) and allocation rate ($AR_{organ}$) of nutrients in each organ of the plant were evaluated according to the following formulas:

$$A_{organ}\ (\text{mg plant}^{-1}) = M_{organ} \times C_{organ} \quad (1)$$

$$AR_{organ}\ (\%) = A_{organ}/A_{plant} \times 100\% \quad (2)$$

where $M_{organ}$ and $C_{organ}$ denote the biomass in each organ of the plant (g) and the nutrient content in each organ of the plant (mg $g^{-1}$), respectively. $A_{organ}$ denotes the accumulation of nutrients in the organ. $A_{plant}$ denotes the accumulation of nutrients in the plant.

### 2.5. Measuring Morphological Characteristics, Dry Matter Quantity, and Peanut Yield

During the plants' maturity, three plants were sampled from each treatment; the main stem height, the lateral branch length, and the number of total branches were measured. In addition, three representative plants from each treatment were selected and divided into vegetative and reproductive organs. The weights were measured after being placed in an oven at 105 °C for 30 min and drying at 80 °C.

At plant maturity, plants from each treatment were collected and weighed to obtain the yield and yield components.

### 2.6. Data Analysis

All the parameters were measured for a minimum of three biological replicates and were analyzed with SPSS Statistics 26.0 (IBM, Armonk, NY, USA). The impacts of calcium and nitrogen fertilizers and their interactions were investigated using a two-way analysis of variance (ANOVA) following the least significant difference (LSD) method. The different lowercase letters indicate significant differences at $p < 0.05$. * and ** represent $p < 0.05$ and $p < 0.01$. The significance of the linear relationships between the obtained variables was analyzed using Pearson's correlation analysis by IBM SPSS Statistics 26.0. The relationship between the fertilizers' application and relative yield was plotted using Origin 2021 (OriginLab, Northampton, MA, USA). The linear-plateau model was used to fit the corresponding data [30]. The figures including the heat map were designed by Origin 2021.

## 3. Results

### *3.1. Net Photosynthetic Rate*

The application of calcium and nitrogen fertilizers significantly impacted the net photosynthetic rate (*Pn*) of peanut leaves; their interaction also demonstrated a significant effect (Figure 2). The application of calcium fertilizer increased *Pn* by 6.5–27.6% in 2015 and 6.9–16.6% in 2016, compared to that of $Ca_0$. The application of nitrogen fertilizer increased *Pn* by 9.0–46.1% in 2015 and 22.6–50.9% in 2016, compared to that of $N_0$. The highest *Pn* was observed with the application of $Ca_1$ and $N_{135.0}$ fertilizers.

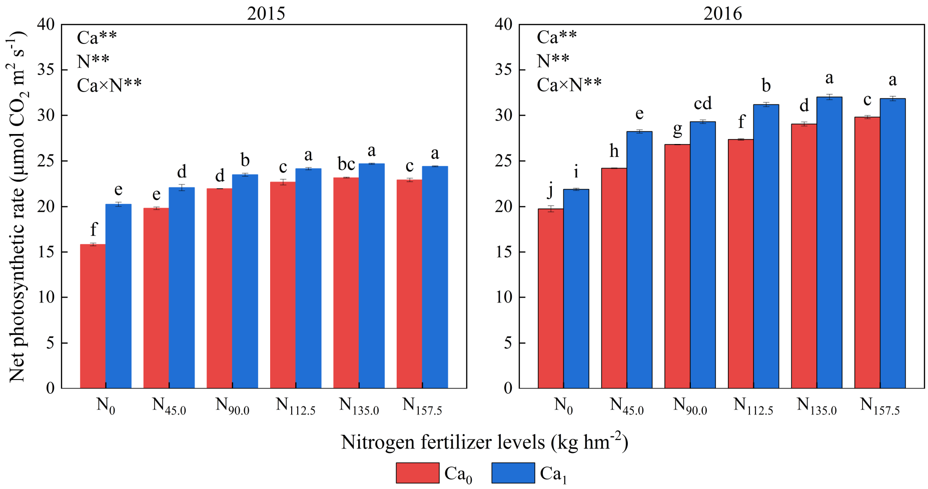


**Figure 2.** Effects of calcium ($Ca_0$: 0 and $Ca_1$: 568 kg CaO·ha$^{-1}$) and nitrogen ($N_0$: 0, $N_{45.0}$: 45.0, $N_{90.0}$: 90.0, $N_{112.5}$: 112.5, $N_{135.0}$: 135.0, and $N_{157.5}$: 157.5 kg N ha$^{-1}$) fertilizers' application on net photosynthetic rate (*Pn*) of peanut leaves in 2015 and 2016. Vertical bars denote standard error ($n$ = 6). Lowercase letters indicate significant differences at $p < 0.05$. Two-way analysis of variance was performed to evaluate the effects of calcium (Ca), nitrogen (N), and their interactions (Ca × N). ** indicates significant difference at $p < 0.01$ probability levels.

### *3.2. Agronomic Traits and Dry Matter Quality*

The application of calcium fertilizer significantly impacted the main stem height, lateral branch length, and dry matter quality of the peanut plants, whereas the application of nitrogen fertilizer had a significant effect on the main stem height and the dry matter quality. However, there was no significant interaction between them (Table 2).

Compared to $Ca_0$, the addition of calcium increased the dry matter weight of the vegetative and reproductive organs by 4.8–13.0% and 5.9–20.3% in 2015, respectively, and by 17.3–27.2% and 9.1–12.1% in 2016, respectively. In comparison, the addition of nitrogen increased the dry matter weight of the vegetative and reproductive organs by 58.3–136.2% and 59.5–152.7% in 2015, respectively, and by 18.3–71.6% and 10.4–48.8% in 2016, respectively, compared to $N_0$. However, no significant difference in dry matter quality was observed between high nitrogen levels, such as $N_{135.0}$ and $N_{157.5}$.

### *3.3. Peanut Yield and Yield Components*

The application of nitrogen and calcium fertilizers, as well as their interaction, had a significant impact on the peanut pod yield (Table 3). For $Ca_0$ treatments, the pod yield increased gradually with increasing nitrogen rates in the range of 0–112.5 kg ha$^{-1}$; the $N_{112.5}$ treatment had the highest pod yield, improving it by 52.3% and 138.0% in 2015 and 2016, respectively, compared to that of $N_0$. However, excessive nitrogen application (N > 112.5 kg ha$^{-1}$) did not affect or even reduced the pod yield. For $Ca_1$ treatment, the pod yield increased gradually with increasing nitrogen rates, but there was no significant difference with $N_{112.5}$, $N_{135.0}$, and $N_{157.5}$. At the same nitrogen fertilizer level, the pod yield with $Ca_1$ was significantly higher than that with $Ca_0$ at an increase of 11.5–25.8% in 2015 and 14.7–29.6% in 2016.

**Table 2.** Effects of calcium ($Ca_0$ and $Ca_1$: 568.0 kg CaO $ha^{-1}$) and nitrogen (0, 45, 90, 112.5, 135, and 157.5 kg N $ha^{-1}$) fertilizers' application on the agronomic traits and dry matter quality in 2015 and 2016.

| Ca Fertilizer Level | N Fertilizer Level (kg N $ha^{-1}$) | 2015 | | | | | | 2016 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Main Stem Height (cm) | Lateral Branch Length (cm) | Total Branch Number (No. $Plant^{-1}$) | Dry Matter Weight of Vegetative Organs (g $Plant^{-1}$) | Dry Matter Weight of Reproductive Organs (g $Plant^{-1}$) | Total dry Matter Weight (g $Plant^{-1}$) | Main Stem Height (cm) | Lateral Branch Length (cm) | Total Branch Number (No. $Plant^{-1}$) | Dry Matter Weight of Vegetative Organs (g $Plant^{-1}$) | Dry Matter Weight of Reproductive Organs (g $Plant^{-1}$) | Total Dry Matter Weight (g $Plant^{-1}$) |
| $Ca_0$ | 0 | 14.1 ± 0.4 c | 15.3 ± 0.5 c | 7.8 ± 0.5 ab | 7.7 ± 0.2 e | 6.6 ± 0.1 e | 14.2 ± 0.3 e | 20.9 ± 0.8 b | 27.1 ± 1.7 c | 7.3 ± 0.8 a | 14.3 ± 0.7 c | 17.8 ± 0.2 e | 32.1 ± 0.9 d |
| | 45 | 20.7 ± 1.0 b | 22.6 ± 0.5 b | 9.0 ± 0.1 a | 12.3 ± 0.7 d | 10.5 ± 0.2 d | 22.8 ± 1.0 d | 22.7 ± 0.6 b | 29.6 ± 1.2 c | 7.8 ± 0.8 a | 17.0 ± 0.7 b | 20.2 ± 0.3 d | 37.2 ± 0.8 c |
| | 90 | 22.2 ± 0.4 b | 25.1 ± 0.7 ab | 7.8 ± 0.9 ab | 14.6 ± 0.4 c | 14.0 ± 0.4 c | 28.6 ± 0.8 c | 29.5 ± 0.9 a | 35.3 ± 0.4 b | 8.8 ± 0.3 a | 22.0 ± 0.4 a | 24.2 ± 0.4 c | 46.2 ± 0.8 b |
| | 112.5 | 22.5 ± 0.6 b | 25.3 ± 0.4 a | 7.5 ± 0.5 ab | 15.3 ± 0.4 bc | 15.6 ± 0.1 b | 30.9 ± 0.4 b | 30.4 ± 0.7 a | 35.4 ± 0.9 b | 8.5 ± 0.6 a | 22.4 ± 0.9 a | 25.1 ± 0.1 bc | 47.5 ± 0.9 ab |
| | 135 | 22.8 ± 0.3 ab | 26.2 ± 1.3 a | 7.5 ± 0.5 ab | 16.4 ± 0.6 ab | 16.5 ± 0.2 a | 32.9 ± 0.7 a | 30.3 ± 0.7 a | 35.6 ± 0.7 b | 8.5 ± 0.6 a | 23.4 ± 0.9 a | 26.1 ± 0.3 ab | 49.5 ± 1.2 a |
| | 157.5 | 25.4 ± 1.5 a | 27.6 ± 0.9 a | 6.8 ± 0.5 b | 17.7 ± 0.2 a | 16.6 ± 0.2 a | 34.3 ± 0.4 a | 31.4 ± 0.7 a | 39.4 ± 0.9 a | 8.5 ± 0.3 a | 23.6 ± 0.5 a | 26.5 ± 0.6 a | 50.1 ± 1.0 a |
| $Ca_1$ | 0 | 15.9 ± 0.3 d | 17.2 ± 0.1 d | 8.8 ± 0.3 a | 8.1 ± 0.2 d | 7.6 ± 0.1 e | 15.8 ± 0.3 e | 24.6 ± 0.4 d | 32.6 ± 1.2 b | 8.3 ± 0.3 a | 16.8 ± 0.3 d | 20.0 ± 0.1 d | 36.8 ± 0.3 d |
| | 45 | 20.5 ± 1.0 c | 20.9 ± 1.0 c | 9.3 ± 0.3 a | 12.9 ± 0.2 c | 12.6 ± 0.2 d | 25.5 ± 0.4 d | 28.3 ± 0.4 c | 33.8 ± 1.4 b | 8.3 ± 0.9 a | 21.6 ± 0.5 c | 22.0 ± 0.1 c | 43.6 ± 0.6 c |
| | 90 | 23.0 ± 0.8 b | 25.6 ± 0.9 b | 9.3 ± 0.3 a | 16.0 ± 0.3 b | 15.6 ± 0.1 c | 31.7 ± 0.4 c | 30.7 ± 1.3 bc | 36.9 ± 2.9 ab | 9.0 ± 0.7 a | 26.2 ± 0.6 b | 26.4 ± 0.2 b | 52.6 ± 0.7 b |
| | 112.5 | 25.3 ± 0.4 a | 27.6 ± 0.3 ab | 9.5 ± 0.3 a | 17.0 ± 0.7 b | 16.6 ± 0.2 b | 33.6 ± 0.6 b | 33.3 ± 1.2 ab | 39.5 ± 1.9 a | 9.3 ± 0.3 a | 28.1 ± 0.7 ab | 28.0 ± 0.5 a | 56.1 ± 0.4 a |
| | 135 | 25.5 ± 0.4 a | 27.8 ± 0.5 a | 9.0 ± 0.4 a | 18.5 ± 0.6 a | 17.5 ± 0.2 a | 36.0 ± 0.4 a | 34.4 ± 0.6 a | 41.6 ± 1.2 a | 8.8 ± 0.6 a | 28.7 ± 1.1 a | 29.0 ± 0.4 a | 57.7 ± 0.9 a |
| | 157.5 | 25.5 ± 0.4 a | 28.0 ± 0.8 a | 8.8 ± 0.3 a | 19.2 ± 0.4 a | 17.7 ± 0.2 a | 36.9 ± 0.2 a | 35.7 ± 0.8 a | 42.0 ± 0.3 a | 8.5 ± 0.3 a | 28.8 ± 0.7 a | 29.1 ± 0.5 a | 57.9 ± 1.2 a |
| Significance of factors | | | | | | | | | | | | | |
| Ca | | ** | NS | ** | ** | ** | ** | ** | ** | NS | ** | ** | ** |
| N | | ** | ** | NS | ** | ** | ** | ** | ** | NS | ** | ** | ** |
| Ca × N | | NS | NS | NS | NS | * | NS | NS | NS | NS | NS | NS | NS |

Data are presented as mean ± SE, $n$ = 3. Values followed by different lowercase letters in the same column were significantly different among treatments at 0.05 level for the same factor. Two-way analysis of variance was performed to evaluate the effects of calcium (Ca), nitrogen (N), and their interactions (Ca × N). NS means non-significant. * and ** indicate significant difference at $p < 0.05$ and $p < 0.01$ probability levels, respectively.

**Table 3.** Effects of calcium ($Ca_0$ and $Ca_1$: 568.0 kg CaO $ha^{-1}$) and nitrogen (0, 45, 90, 112.5, 135, and 157.5 kg N $ha^{-1}$) fertilizers' application on peanut yield and yield components in 2015 and 2016.

| Ca Fertilizer Level | N Fertilizer Level (kg N $ha^{-1}$) | 2015 Pod Yield (kg·$ha^{-1}$) | 2015 Full-Pod Number (No. $Plant^{-1}$) | 2015 Non-Full-Pod Number (No. $Plant^{-1}$) | 2015 100-Pod Weight (g) | 2015 Kernel Rate (%) | 2016 Pod Yield (kg·$ha^{-1}$) | 2016 Full-Pod Number (No. $Plant^{-1}$) | 2016 Non-Full-Pod Number (No. $Plant^{-1}$) | 2016 100-Pod Weight (g) | 2016 Kernel Rate (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $Ca_0$ | 0 | 1140 ± 80 c | 2.7 ± 0.2 c | 5.4 ± 0.2 c | 90.6 ± 3.0 c | 72.3 ± 0.6 a | 3158 ± 90 d | 9.3 ± 0.1 c | 6.7 ± 0.7 b | 107.5 ± 0.6 c | 73.7 ± 0.4 a |
| | 45 | 1862 ± 120 b | 3.4 ± 0.1 b | 8.3 ± 0.5 b | 104.2 ± 1.2 a | 72.2 ± 0.5 a | 3636 ± 74 c | 9.8 ± 0.2 c | 8.5 ± 0.3 ab | 112.8 ± 1.4 b | 73.1 ± 0.2 ab |
| | 90 | 2524 ± 87 a | 3.8 ± 0.1 ab | 11.9 ± 0.2 a | 103.4 ± 1.7 ab | 72.4 ± 0.4 a | 4593 ± 66 ab | 12.1 ± 0.5 b | 9.8 ± 1.0 ab | 112.6 ± 0.8 b | 73.1 ± 0.4 ab |
| | 112.5 | 2712 ± 61 a | 4.5 ± 0.3 a | 12.6 ± 0.7 a | 97.4 ± 4.0 abc | 71.7 ± 0.6 a | 4810 ± 78 a | 13.3 ± 0.5 a | 7.8 ± 1.0 b | 118.5 ± 1.4 a | 73.3 ± 0.3 ab |
| | 135 | 2563 ± 63 a | 4.0 ± 0.3 ab | 12.8 ± 0.8 a | 94.8 ± 1.1 bc | 71.6 ± 1.2 a | 4701 ± 97 ab | 12.0 ± 0.3 b | 9.7 ± 1.2 ab | 114.1 ± 1.9 b | 72.8 ± 0.4 ab |
| | 157.5 | 2540 ± 54 a | 3.6 ± 0.2 b | 13.6 ± 0.7 a | 89.0 ± 3.1 c | 72.6 ± 0.8 a | 4484 ± 126 b | 11.5 ± 0.1 b | 11.0 ± 0.6 a | 110.0 ± 0.2 bc | 71.7 ± 0.8 b |
| $Ca_1$ | 0 | 1312 ± 37 d | 2.8 ± 0.1 d | 4.8 ± 0.3 c | 109.7 ± 1.4 b | 70.3 ± 1.0 a | 3623 ± 36 d | 9.7 ± 0.2 c | 9.2 ± 0.6 bc | 111.0 ± 1.1 c | 72.3 ± 0.7 a |
| | 45 | 2198 ± 26 c | 3.3 ± 0.1 d | 10.0 ± 0.1 b | 110.4 ± 1.8 b | 72.2 ± 0.9 a | 4312 ± 101 c | 10.6 ± 0.4 c | 8.3 ± 0.7 c | 120.7 ± 1.0 a | 72.3 ± 0.5 a |
| | 90 | 2814 ± 58 b | 5.2 ± 0.3 c | 12.0 ± 0.5 a | 115.1 ± 2.6 ab | 72.3 ± 0.8 a | 5345 ± 37 b | 13.5 ± 0.4 b | 10.3 ± 1.2 bc | 121.9 ± 1.1 a | 72.8 ± 0.8 a |
| | 112.5 | 3126 ± 44 a | 6.8 ± 0.1 a | 9.8 ± 0.3 b | 121.1 ± 2.4 a | 72.3 ± 0.8 a | 5723 ± 151 a | 13.8 ± 0.2 b | 11.7 ± 0.3 b | 122.7 ± 0.4 a | 72.3 ± 0.9 a |
| | 135 | 3168 ± 32 a | 5.9 ± 0.1 b | 11.7 ± 0.3 a | 119.8 ± 2.9 a | 71.3 ± 1.4 a | 5800 ± 147 a | 13.9 ± 0.2 b | 14.3 ± 1.0 a | 116.5 ± 0.7 b | 72.2 ± 1.0 a |
| | 157.5 | 3195 ± 65 a | 6.0 ± 0.1 b | 12.3 ± 0.1 a | 118.9 ± 1.1 a | 70.5 ± 0.1 a | 5811 ± 149 a | 15.3 ± 0.3 a | 11.5 ± 0.6 b | 113.2 ± 0.4 c | 72.5 ± 0.3 a |
| Significance of factors | | | | | | | | | | | |
| Ca | | ** | ** | * | ** | NS | ** | ** | ** | ** | NS |
| N | | ** | ** | ** | ** | NS | ** | ** | ** | ** | NS |
| Ca × N | | ** | ** | ** | ** | NS | ** | ** | * | * | NS |

Data are presented as mean ± SE, $n = 3$. Values followed by different lowercase letters in the same column were significantly different among treatments at the 0.05 level for the same factor. Two-way analysis of variance was performed to evaluate the effects of calcium (Ca), nitrogen (N), and their interactions (Ca × N). NS means non-significant. * and ** indicate significant difference at $p < 0.05$ and $p < 0.01$ probability levels, respectively.

The use of nitrogen and calcium fertilizers and their interaction also had significant effects on yield components, except for the kernel rate. Calcium application significantly increased the number of full pods per plant and the 100-pod weight. With increasing nitrogen rates, the number of full pods per plant and the 100-pod weight first increased and then decreased, reaching a peak at $N_{112.5}$, except for the 100-pod weight under $Ca_0$ in 2015 and the number of full pods per plant under $Ca_1$ in 2016.

*3.4. Nutrient Accumulation of a Single Peanut Plant*

The application of calcium or nitrogen fertilizer significantly affected the nutrient accumulation of single peanut plants, with a significant interaction between them observed for calcium accumulation in 2015 (Figure 3).

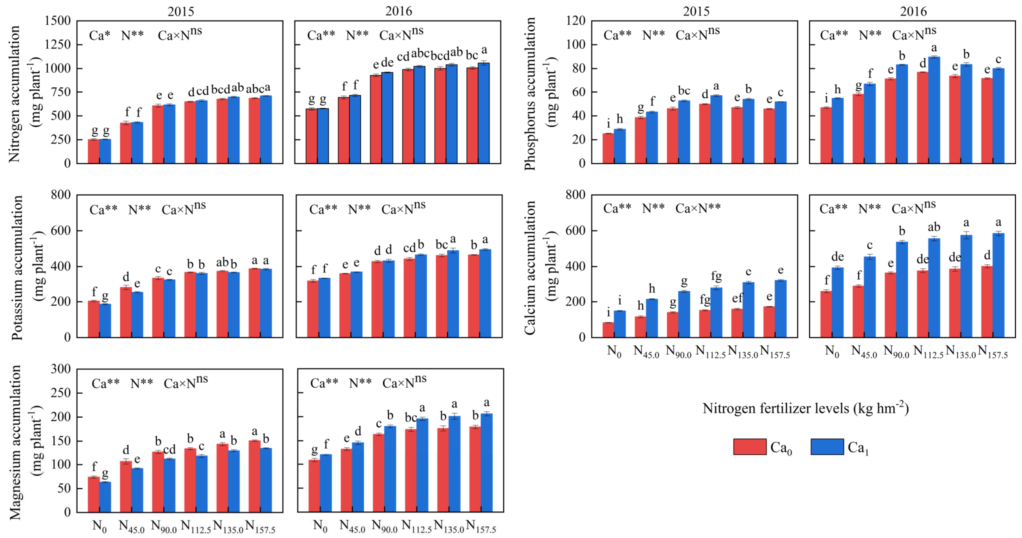


**Figure 3.** Effects of calcium ($Ca_0$: 0 and $Ca_1$: 568 kg CaO·ha$^{-1}$) and nitrogen ($N_0$: 0, $N_{45.0}$: 45.0, $N_{90.0}$: 90.0, $N_{112.5}$: 112.5, $N_{135.0}$: 135.0, and $N_{157.5}$: 157.5 kg N ha$^{-1}$) fertilizers' application on nutrient accumulation of single peanut plants in 2015 and 2016. Vertical bars denote standard error ($n$ = 3). Lowercase letters indicate significant differences at $p < 0.05$. Two-way analysis of variance was performed to evaluate the effects of calcium (Ca), nitrogen (N), and their interactions (Ca × N). ns means non-significant. * and ** indicate significant difference at $p < 0.05$ and $p < 0.01$ probability levels, respectively.

The application of calcium increased nitrogen accumulation, with a significant difference between $Ca_1$ and $Ca_0$ observed in 2016 for the $N_{157.5}$ treatment. The application of nitrogen significantly increased nitrogen accumulation under the same calcium treatment, but no significant difference was detected with $N_{112.5}$, $N_{135.0}$, and $N_{157.5}$. Calcium application also significantly increased phosphorus accumulation under the same nitrogen treatment, with a peak value obtained at an application rate of 112.5 kg ha$^{-1}$. $Ca_1$ increased phosphorus accumulation by 14.35% and 14.25% in 2015 and 2016, respectively, compared to $Ca_0$.

Potassium accumulation did not differ significantly between $Ca_1$ and $Ca_0$ under the same nitrogen treatment but increased with increasing nitrogen fertilizer. The use of calcium or nitrogen increased calcium accumulation, with no significant differences observed between $N_{112.5}$, $N_{135}$, and $N_{157.5}$ under the same calcium treatment. The effect of calcium on magnesium accumulation under the same nitrogen treatment was not consistent in 2015 and 2016, but magnesium accumulation increased with increasing nitrogen under the same calcium treatment.

### *3.5. Nutrient Accumulation and Distribution of Peanut Organs*

#### 3.5.1. Nitrogen Accumulation and Distribution

The calcium and nitrogen fertilizers had significant effects on nitrogen accumulation and distribution in the different organs of the peanut plant; their interaction only affected nitrogen accumulation and distribution in the peg, husk, and kernel (Table 4).

The application of calcium increased the accumulation of nitrogen in the kernel, resulting in a 5.1–16.7% increase in 2015 and an 8.0–22.7% increase in 2016, compared to $Ca_0$. However, there was no significant difference in nitrogen accumulation in the vegetative organs, peg, and husk between $Ca_0$ and $Ca_1$. Under the same calcium treatment, nitrogen accumulation in the vegetative organs only varied significantly between $N_0$ and $N_{45}$, while nitrogen accumulation in the peg and husk increased with increasing nitrogen. However, there was no significant difference in nitrogen accumulation in the kernel between the $N_{112.5}$, $N_{135.0}$, and $N_{157.5}$ treatments.

With the application of calcium, nitrogen distribution in the vegetative and reproductive organs decreased, while nitrogen distribution in the kernels increased. There was no significant difference in nitrogen distribution in the vegetative organs and kernels under nitrogen treatments. Only under $Ca_1$ did nitrogen distribution in the peg and husk decrease initially, which then subsequently increased with increasing nitrogen.

#### 3.5.2. Phosphorus Accumulation and Distribution

Both calcium and nitrogen fertilizers had significant effects on the accumulation and distribution of phosphorus in the different organs, while the interaction effect only affected accumulation in the peg, husk, and kernel (Table 5).

The application of calcium significantly increased phosphorus accumulation in the kernel by 27.8–34.9% and 27.3–34.7% in 2015 and 2016, respectively, while the difference in phosphorus accumulation in the vegetative organs, peg, and husk between $Ca_1$ and $Ca_0$ was not significant. Under the same calcium treatment, phosphorus accumulation in the vegetative organs, peg, and husk was significantly different between the $N_0$ and $N_{45}$ treatments. Phosphorus accumulation in the kernel first increased and then decreased with increasing nitrogen fertilizer; the highest phosphorus accumulation was observed at a nitrogen application rate of 112.5 kg $ha^{-1}$.

With the application of calcium, phosphorus distribution in the vegetative and reproductive organs decreased, while it increased in the kernel. However, with the application of nitrogen, there was a small difference in phosphorus distribution in the vegetative organs, peg, husk, and kernel.

#### 3.5.3. Potassium Accumulation and Distribution

The application of calcium and nitrogen fertilizers had a significant impact on the accumulation and distribution of potassium in the different organs, while their interaction only affected the accumulation in the kernel (Table 6).

Calcium application significantly increased the accumulation of potassium in the kernel, with an increase of 6.8–22.9% in 2015 and 10.6–35.9% in 2016; the accumulation of potassium was reduced in the vegetative organs, peg, and husk. Under the same calcium treatment, the accumulation of potassium in the vegetative organs, peg, and husk increased significantly, while in the kernel, it increased initially and then decreased with increasing nitrogen fertilizer. The highest accumulation of potassium in the kernel was observed at a nitrogen rate of 112.5 kg $ha^{-1}$.

With the application of nitrogen, the distribution of potassium in the vegetative and reproductive organs decreased, while it increased in the kernel. With the application of nitrogen, there was a small difference in the potassium distribution in the vegetative organs, peg, and husk. The distribution of potassium in the kernel increased initially and then decreased with increasing nitrogen application, but the difference among treatments was also small.

**Table 4.** Effects of calcium ($Ca_0$ and $Ca_1$: 568.0 kg CaO $ha^{-1}$) and nitrogen (0, 45, 90, 112.5, 135, and 157.5 kg N $ha^{-1}$) fertilizers' application on nitrogen accumulation and distribution in 2015 and 2016.

| Ca Fertilizer Level | N Fertilizer Level (kg N $ha^{-1}$) | 2015 | | | | | | 2016 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $A_V$ (g $Plant^{-1}$) | $AR_V$ (%) | $A_P$ (g $Plant^{-1}$) | $AR_P$ (%) | $A_K$ (g $Plant^{-1}$) | $AR_K$ (%) | $A_V$ (g $Plant^{-1}$) | $AR_V$ (%) | $A_P$ (g $Plant^{-1}$) | $AR_P$ (%) | $A_K$ (g $Plant^{-1}$) | $AR_K$ (%) |
| $Ca_0$ | 0 | 92.8 ± 2.3 c | 36.9 ± 0.3 b | 49.3 ± 3.1 f | 19.7 ± 1.9 a | 109.2 ± 8.5 c | 43.3 ± 2.1 a | 169.3 ± 6.8 c | 29.6 ± 0.9 b | 117.7 ± 3.2 d | 20.6 ± 0.2 ab | 284.9 ± 6.7 d | 49.8 ± 0.8 a |
| | 45 | 162.5 ± 9.8 b | 38.2 ± 0.6 b | 75.4 ± 2.2 e | 17.9 ± 1.3 ab | 186.8 ± 12.1 b | 43.9 ± 1.1 a | 211.7 ± 10.8 b | 30.6 ± 1.0 ab | 133.9 ± 2.7 cd | 19.4 ± 0.7 b | 346.5 ± 8.0 c | 50.1 ± 0.4 a |
| | 90 | 248.3 ± 6.7 a | 40.9 ± 0.5 a | 93.4 ± 3.4 d | 15.4 ± 0.2 b | 265.0 ± 7.7 a | 43.7 ± 0.7 a | 303.5 ± 5.6 a | 32.7 ± 0.2 a | 152.6 ± 7.8 c | 16.4 ± 0.7 c | 472.8 ± 4.9 b | 50.9 ± 0.6 a |
| | 112.5 | 253.8 ± 5.8 a | 39.2 ± 0.9 ab | 106.7 ± 1.6 c | 16.5 ± 0.2 b | 287.5 ± 7.1 a | 44.4 ± 1.1 a | 320.5 ± 12.9 a | 32.4 ± 0.9 a | 159.2 ± 3.9 bc | 16.1 ± 0.6 c | 510.4 ± 9.4 a | 51.6 ± 0.8 a |
| | 135 | 258.5 ± 7.6 a | 38.3 ± 0.9 b | 133.0 ± 3.9 b | 19.7 ± 0.5 a | 283.9 ± 8.8 a | 42.0 ± 1.3 a | 313.4 ± 11.3 a | 31.3 ± 0.6 ab | 185.2 ± 3.0 b | 18.5 ± 0.3 bc | 502.3 ± 7.4 a | 50.2 ± 0.6 a |
| | 157.5 | 258.2 ± 3.5 a | 37.7 ± 0.5 b | 144.5 ± 4.3 a | 21.1 ± 0.6 a | 281.6 ± 7.7 a | 41.2 ± 1.1 a | 314.5 ± 6.2 a | 31.2 ± 0.2 ab | 224.8 ± 17.8 a | 22.3 ± 1.7 a | 467.4 ± 17.8 b | 46.4 ± 1.8 b |
| $Ca_1$ | 0 | 89.4 ± 1.9 c | 35.3 ± 0.3 b | 49.0 ± 0.5 e | 19.4 ± 0.5 a | 114.8 ± 2.7 d | 45.3 ± 0.4 b | 151.8 ± 3.7 c | 26.3 ± 0.6 b | 116.4 ± 2.4 c | 20.2 ± 0.4 a | 307.8 ± 5.3 d | 53.4 ± 0.9 a |
| | 45 | 153.6 ± 1.9 b | 35.7 ± 0.2 ab | 73.9 ± 2.4 d | 17.2 ± 0.5 bc | 203.1 ± 4.5 c | 47.2 ± 0.7 ab | 207.5 ± 5.9 b | 29.1 ± 0.3 a | 123.9 ± 0.7 bc | 17.4 ± 0.4 b | 382.4 ± 7.2 c | 53.6 ± 0.2 a |
| | 90 | 234.8 ± 5.9 a | 38.2 ± 0.4 a | 89.5 ± 0.9 c | 14.6 ± 0.3 d | 290.8 ± 5.5 b | 47.3 ± 0.5 ab | 293.6 ± 4.8 a | 30.6 ± 0.4 a | 140.9 ± 8.4 bc | 14.7 ± 0.8 c | 524.4 ± 8.6 b | 54.7 ± 1.1 a |
| | 112.5 | 236.8 ± 10.6 a | 35.9 ± 1.2 ab | 95.9 ± 0.8 c | 14.6 ± 0.1 d | 325.7 ± 4.0 a | 49.5 ± 1.1 a | 312.9 ± 8.1 a | 30.6 ± 1.0 a | 143.7 ± 2.5 bc | 14.1 ± 0.3 c | 566.3 ± 17.9 a | 55.3 ± 1.3 a |
| | 135 | 252.0 ± 8.1 a | 36.1 ± 0.8 ab | 113.8 ± 6.2 b | 16.3 ± 1.1 c | 331.4 ± 9.0 a | 47.5 ± 1.0 ab | 310.5 ± 11.1 a | 29.9 ± 1.2 a | 155.8 ± 1.6 b | 15.0 ± 0.3 c | 574.0 ± 20.1 a | 55.2 ± 1.4 a |
| | 157.5 | 250.9 ± 5.2 a | 35.4 ± 0.9 b | 130.8 ± 2.8 a | 18.4 ± 0.3 ab | 327.5 ± 6.0 a | 46.2 ± 0.7 b | 310.2 ± 6.8 a | 29.3 ± 0.4 a | 174.6 ± 4.5 a | 16.5 ± 0.1 b | 573.7 ± 12.7 a | 54.2 ± 0.3 a |
| Significance of factors | | | | | | | | | | | | | |
| Ca | | * | ** | ** | ** | ** | ** | NS | ** | ** | ** | ** | ** |
| N | | ** | ** | ** | ** | ** | NS | ** | ** | ** | ** | ** | NS |
| Ca × N | | NS | NS | * | NS | NS | NS | NS | NS | * | * | * | NS |

$A_V$, $A_P$, and $A_K$ stand for the accumulation of nutrients in the vegetative organs, peg and husk, and kernel of the plant, respectively. $AR_V$, $AR_P$, and $AR_K$ stand for the allocation rate of nutrients in the vegetative organs, peg and husk, and kernel of the plant, respectively. Data are presented as mean ± SE, $n$ = 3. Values followed by different lowercase letters in the same column were significantly different among treatments at the 0.05 level for the same factor. Two-way analysis of variance was performed to evaluate the effects of calcium (Ca), nitrogen (N), and their interactions (Ca × N). NS means non-significant. * and ** indicate significant difference at $p < 0.05$ and $p < 0.01$ probability levels, respectively.

**Table 5.** Effects of calcium ($Ca_0$ and $Ca_1$: 568.0 kg CaO $ha^{-1}$) and nitrogen (0, 45, 90, 112.5, 135, and 157.5 kg N $ha^{-1}$) fertilizers' application on phosphorus accumulation and distribution in 2015 and 2016.

| Ca Fertilizer Level | N Fertilizer Level (kg N $ha^{-1}$) | 2015 | | | | | | 2016 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $A_V$ (g $Plant^{-1}$) | $AR_V$ (%) | $A_P$ (g $Plant^{-1}$) | $AR_P$ (%) | $A_K$ (g $Plant^{-1}$) | $AR_K$ (%) | $A_V$ (g $Plant^{-1}$) | $AR_V$ (%) | $A_P$ (g $Plant^{-1}$) | $AR_P$ (%) | $A_K$ (g $Plant^{-1}$) | $AR_K$ (%) |
| $Ca_0$ | 0 | 8.9 ± 0.1 c | 35.3 ± 0.6 a | 4.0 ± 0.1 d | 15.8 ± 0.2 ab | 12.3 ± 0.4 d | 48.9 ± 0.8 c | 15.0 ± 0.1 c | 31.9 ± 0.6 a | 7.2 ± 0.2 e | 15.3 ± 0.5 a | 24.7 ± 0.7 d | 52.7 ± 0.8 c |
| | 45 | 12.0 ± 0.7 b | 31.0 ± 1.3 b | 5.6 ± 0.1 c | 14.6 ± 0.7 abc | 21.0 ± 0.6 c | 54.4 ± 1.0 ab | 17.3 ± 0.4 b | 29.8 ± 0.1 b | 8.0 ± 0.2 d | 13.7 ± 0.3 b | 32.8 ± 0.8 c | 56.5 ± 0.4 ab |
| | 90 | 13.4 ± 0.4 a | 29.1 ± 0.5 b | 6.6 ± 0.2 b | 14.4 ± 0.2 c | 26.0 ± 0.8 b | 56.6 ± 0.7 a | 20.2 ± 0.4 a | 28.4 ± 0.2 b | 9.3 ± 0.1 c | 13.1 ± 0.1 b | 41.8 ± 0.4 b | 58.6 ± 0.3 ab |
| | 112.5 | 14.3 ± 0.2 a | 28.7 ± 0.5 b | 7.2 ± 0.1 a | 14.6 ± 0.2 bc | 28.3 ± 0.5 a | 56.8 ± 0.7 a | 21.5 ± 0.9 a | 27.9 ± 1.1 b | 10.2 ± 0.4 b | 13.3 ± 0.5 b | 45.2 ± 0.6 a | 58.8 ± 1.0 a |
| | 135 | 14.3 ± 0.4 a | 30.5 ± 0.7 b | 7.5 ± 0.2 a | 16.0 ± 0.4 a | 25.1 ± 0.6 b | 53.5 ± 1.0 b | 20.9 ± 0.8 a | 28.4 ± 0.5 b | 11.0 ± 0.2 a | 14.9 ± 0.3 a | 41.8 ± 0.6 b | 56.8 ± 0.6 ab |
| | 157.5 | 14.1 ± 0.2 a | 30.9 ± 0.6 b | 7.3 ± 0.1 a | 15.9 ± 0.4 ab | 24.4 ± 0.7 b | 53.2 ± 1.0 b | 20.3 ± 0.4 a | 28.3 ± 0.4 b | 11.0 ± 0.2 a | 15.3 ± 0.4 a | 40.4 ± 0.5 b | 56.3 ± 0.5 b |
| $Ca_1$ | 0 | 8.5 ± 0.2 c | 29.7 ± 0.3 a | 3.6 ± 0.1 c | 12.5 ± 0.2 a | 16.6 ± 0.5 e | 57.7 ± 0.5 d | 13.1 ± 0.1 c | 23.9 ± 0.2 a | 8.3 ± 0.1 d | 15.3 ± 0.3 a | 33.3 ± 0.6 e | 60.9 ± 0.5 d |
| | 45 | 10.5 ± 0.1 b | 24.3 ± 0.2 bc | 5.9 ± 0.2 b | 13.6 ± 0.3 a | 26.8 ± 0.6 d | 62.1 ± 0.5 bc | 15.4 ± 0.4 b | 23.0 ± 0.2 ab | 9.1 ± 0.2 cd | 13.6 ± 0.1 b | 42.6 ± 0.8 d | 63.4 ± 0.2 c |
| | 90 | 12.3 ± 0.3 a | 23.5 ± 0.3 c | 6.9 ± 0.1 a | 13.1 ± 0.4 a | 33.4 ± 0.6 b | 63.4 ± 0.5 ab | 18.9 ± 0.3 a | 22.7 ± 0.4 ab | 9.7 ± 0.5 bc | 11.7 ± 0.7 c | 54.6 ± 0.9 b | 65.6 ± 1.0 ab |
| | 112.5 | 13.4 ± 0.6 a | 23.6 ± 0.8 c | 7.2 ± 0.1 a | 12.6 ± 0.2 a | 36.3 ± 0.1 a | 63.8 ± 0.6 a | 19.4 ± 0.5 a | 21.6 ± 0.6 b | 10.7 ± 0.2 a | 11.9 ± 0.2 c | 59.7 ± 1.2 a | 66.5 ± 0.8 a |
| | 135 | 13.4 ± 0.4 a | 24.8 ± 0.5 bc | 7.0 ± 0.3 a | 12.9 ± 0.7 a | 33.6 ± 0.6 b | 62.3 ± 0.5 abc | 18.8 ± 0.4 a | 22.5 ± 0.7 ab | 10.7 ± 0.4 a | 12.8 ± 0.6 b | 54.0 ± 1.9 b | 64.7 ± 1.2 abc |
| | 157.5 | 13.2 ± 0.3 a | 25.4 ± 0.5 b | 6.8 ± 0.2 a | 13.2 ± 0.4 a | 31.8 ± 0.1 c | 61.4 ± 0.3 c | 18.2 ± 0.3 a | 22.7 ± 0.5 ab | 10.4 ± 0.3 ab | 13.0 ± 0.5 b | 51.5 ± 1.1 c | 64.3 ± 0.7 bc |
| Significance of factors | | | | | | | | | | | | | |
| Ca | | ** | ** | NS | ** | ** | ** | ** | ** | * | ** | ** | ** |
| N | | ** | ** | ** | NS | ** | ** | ** | ** | ** | ** | ** | ** |
| Ca × N | | NS | NS | * | * | ** | NS | NS | NS | * | NS | * | NS |

$A_V$, $A_P$, and $A_K$, stand for the accumulation of nutrients in the vegetative organs, peg and husk, and kernel of the plant, respectively. $AR_V$, $AR_P$, and $AR_K$ stand for the allocation rate of nutrients in the vegetative organs, peg and husk, and kernel of the plant, respectively. Data are presented as mean ± SE, $n$ = 3. Values followed by different lowercase letters in the same column were significantly different among treatments at the 0.05 level for the same factor. Two-way analysis of variance was performed to evaluate the effects of calcium (Ca), nitrogen (N), and their interactions (Ca × N). NS means non-significant. * and ** indicate significant difference at $p < 0.05$ and $p < 0.01$ probability levels, respectively.

**Table 6.** Effects of calcium ($Ca_0$ and $Ca_1$: 568.0 kg CaO $ha^{-1}$) and nitrogen (0, 45, 90, 112.5, 135, and 157.5 kg N $ha^{-1}$) fertilizers' application on potassium accumulation and distribution in 2015 and 2016.

| Ca Fertilizer Level | N Fertilizer Level (kg N $ha^{-1}$) | 2015 | | | | | | 2016 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $A_V$ (g $Plant^{-1}$) | $AR_V$ (%) | $A_P$ (g $Plant^{-1}$) | $AR_P$ (%) | $A_K$ (g $Plant^{-1}$) | $AR_K$ (%) | $A_V$ (g $Plant^{-1}$) | $AR_V$ (%) | $A_P$ (g $Plant^{-1}$) | $AR_P$ (%) | $A_K$ (g $Plant^{-1}$) | $AR_K$ (%) |
| $Ca_0$ | 0 | 121.5 ± 2.0 e | 59.6 ± 0.2 a | 63.9 ± 2.3 d | 31.3 ± 0.5 a | 18.5 ± 0.4 e | 9.1 ± 0.4 c | 183.4 ± 4.1 b | 57.9 ± 0.6 a | 91.1 ± 4.0 d | 28.7 ± 0.7 ab | 42.5 ± 0.9 e | 13.4 ± 0.1 d |
| | 45 | 162.4 ± 9.8 d | 57.9 ± 1.0 a | 86.4 ± 2.5 c | 30.9 ± 0.6 a | 31.5 ± 0.3 d | 11.3 ± 0.4 ab | 197.4 ± 1.3 b | 55.2 ± 0.6 b | 92.4 ± 1.9 d | 25.8 ± 0.4 c | 67.7 ± 1.6 d | 18.9 ± 0.4 b |
| | 90 | 191.9 ± 5.1 c | 57.7 ± 0.3 a | 101.2 ± 3.6 b | 30.4 ± 0.3 a | 39.5 ± 0.4 c | 11.9 ± 0.3 ab | 231.5 ± 4.3 a | 54.1 ± 0.3 bc | 107.5 ± 1.0 c | 25.1 ± 0.2 c | 88.8 ± 0.9 b | 20.8 ± 0.2 a |
| | 112.5 | 208.5 ± 3.1 bc | 57.1 ± 0.8 a | 112.1 ± 3.1 a | 30.7 ± 0.8 a | 44.3 ± 0.6 a | 12.1 ± 0.2 a | 238.2 ± 9.4 a | 53.8 ± 1.3 bc | 109.8 ± 3.1 c | 24.8 ± 0.8 c | 94.7 ± 1.3 a | 21.4 ± 0.7 a |
| | 135 | 217.5 ± 6.2 ab | 58.2 ± 1.1 a | 113.1 ± 3.6 a | 30.3 ± 1.0 a | 43.0 ± 1.0 ab | 11.5 ± 0.4 ab | 242.1 ± 4.5 a | 52.4 ± 0.2 c | 129.7 ± 2.6 b | 28.1 ± 0.2 b | 89.8 ± 1.3 b | 19.5 ± 0.4 b |
| | 157.5 | 230.9 ± 1.7 a | 59.5 ± 0.6 a | 114.9 ± 3.2 a | 29.6 ± 0.6 a | 42.3 ± 0.4 b | 10.9 ± 0.2 b | 247.4 ± 1.9 a | 53.2 ± 0.6 bc | 139.3 ± 2.2 a | 30.0 ± 0.4 a | 78.5 ± 1.1 c | 16.9 ± 0.2 c |
| $Ca_1$ | 0 | 106.7 ± 2.0 e | 57.2 ± 0.5 ab | 57.1 ± 1.0 e | 30.6 ± 0.4 ab | 22.7 ± 0.1 d | 12.2 ± 0.1 d | 187.3 ± 2.0 d | 56.5 ± 0.7 a | 86.8 ± 3.3 d | 26.1 ± 1.0 a | 57.8 ± 1.1 d | 17.4 ± 0.4 c |
| | 45 | 138.9 ± 1.9 d | 54.9 ± 0.2 b | 80.5 ± 1.7 d | 31.8 ± 0.2 a | 33.6 ± 0.5 c | 13.3 ± 0.1 bc | 201.2 ± 3.1 d | 54.8 ± 0.4 ab | 88.7 ± 1.6 d | 24.2 ± 0.6 bc | 77.0 ± 1.5 c | 21.0 ± 0.3 b |
| | 90 | 184.3 ± 3.3 c | 57.1 ± 0.5 ab | 95.1 ± 2.0 c | 29.5 ± 0.7 bc | 43.5 ± 0.8 b | 13.5 ± 0.3 abc | 229.3 ± 5.3 c | 53.1 ± 0.9 b | 104.6 ± 6.2 c | 24.2 ± 1.0 bc | 98.1 ± 1.3 b | 22.7 ± 0.6 a |
| | 112.5 | 204.5 ± 7.8 b | 56.9 ± 1.4 ab | 103.4 ± 2.4 ab | 28.8 ± 1.0 bc | 51.0 ± 0.6 a | 14.2 ± 0.3 a | 248.2 ± 4.1 b | 53.3 ± 0.6 b | 108.1 ± 1.8 bc | 23.2 ± 0.2 c | 109.2 ± 2.2 a | 23.5 ± 0.6 a |
| | 135 | 212.4 ± 2.3 b | 58.4 ± 0.3 a | 101.7 ± 0.6 b | 28.0 ± 0.2 c | 49.8 ± 1.3 a | 13.7 ± 0.4 ab | 263.1 ± 10.3 ab | 53.8 ± 0.6 b | 115.4 ± 6.3 ab | 23.6 ± 0.9 bc | 110.5 ± 2.9 a | 22.7 ± 1.0 a |
| | 157.5 | 227.2 ± 1.0 a | 59.0 ± 0.4 a | 109.1 ± 2.7 a | 28.3 ± 0.4 c | 48.9 ± 0.9 a | 12.7 ± 0.2 cd | 269.1 ± 3.0 a | 54.4 ± 0.5 b | 124.3 ± 4.6 a | 25.1 ± 0.8 ab | 101.3 ± 0.9 b | 20.5 ± 0.3 b |
| Significance of factors | | | | | | | | | | | | | |
| Ca | | ** | * | ** | ** | ** | ** | ** | NS | ** | ** | ** | ** |
| N | | ** | * | ** | ** | ** | ** | ** | ** | ** | ** | ** | ** |
| Ca × N | | NS | NS | NS | NS | * | NS | NS | NS | NS | * | ** | NS |

$A_V$, $A_P$, and $A_K$ stand for the accumulation of nutrients in the vegetative organs, peg and husk, and kernel of the plant, respectively. $AR_V$, $AR_P$, and $AR_K$ stand for the allocation rate of nutrients in the vegetative organs, peg and husk, and kernel of the plant, respectively. Data are presented as mean ± SE, $n$ = 3. Values followed by different lowercase letters in the same column were significantly different among treatments at the 0.05 level for the same factor. Two-way analysis of variance was performed to evaluate the effects of calcium (Ca), nitrogen (N), and their interactions (Ca × N). NS means non-significant. * and ** indicate significant difference at $p < 0.05$ and $p < 0.01$ probability levels, respectively.

#### 3.5.4. Calcium Accumulation and Distribution

Both calcium and nitrogen application significantly affected the accumulation and distribution of calcium in the different organs, while the interaction effect only significantly impacted calcium accumulation in the kernel (Table 7).

Calcium application significantly increased the accumulation of calcium in the vegetative organs, peg and husk, and kernel. With the same calcium treatment, as the nitrogen application increased, calcium accumulation in the vegetative organs, peg, and husk significantly increased in 2015, while calcium accumulation in the kernel initially increased and then decreased. The highest value of calcium accumulation in the kernel was observed at a nitrogen rate of 112.5 kg ha$^{-1}$.

With the application of calcium, calcium distribution in the peg, husk, and kernel decreased, while calcium distribution in the vegetative organs increased. With nitrogen treatment, there was a minor difference in calcium distribution in the vegetative organs, peg and husk, and kernel.

#### 3.5.5. Magnesium Accumulation and Distribution

Both calcium and nitrogen had significant effects on magnesium accumulation and distribution in the different organs, while the interaction effect only significantly affected magnesium accumulation in the kernel (Table 8).

Calcium significantly promoted magnesium accumulation in the kernel but reduced its accumulation in the peg and husk. However, magnesium accumulation in the vegetative organs was inconsistent in 2015 and 2016. With the same treatment of calcium, magnesium accumulation in the vegetative organs, peg, and husk significantly increased with nitrogen application, while magnesium accumulation in the kernel increased initially and then decreased. The highest magnesium accumulation in the kernel was observed at a nitrogen rate of 112.5 kg ha$^{-1}$.

With the application of calcium, the magnesium distribution increased in the kernel. Under nitrogen treatment, the differences in magnesium distribution in the vegetative organs, peg and husk, and kernel were insignificant.

### *3.6. Pearson's Correlation Analysis and Principal Component Analyses*

To understand the associations between the pod yield under calcium and nitrogen application and the *Pn*, agronomic traits, dry matter quality, and nutrient accumulation and distribution, we performed a Pearson's correlation analysis with the notable traits from the relevant parameters (Figure 4). The peanut pod yield was positively correlated with several traits, including the full-pod number, 100-pod weight, *Pn*, main stem height, total dry matter weight, phosphorus and calcium accumulation in a single plant, and nitrogen, phosphorus, potassium, calcium, and magnesium accumulation in the kernel ($p < 0.01$). However, no significant correlation was observed with the non-full-pod number ($p > 0.05$). These results suggested that the peanut pod yield was influenced by photosynthesis, dry matter quality, and nutrient accumulation when calcium and nitrogen fertilizers were applied.

To further evaluate the overall interactions among all parameters mentioned above related to pod yield, principal component analyses (PCA) were performed using the calcium and nitrogen fertilizer treatments as individuals and all of the relevant parameters as variables (Figure 5). Principal components (PC) 1 and 2 represented 91.5% and 4.9% of the total variance, respectively. The PCA revealed that $Ca_0$ and $Ca_1$ had different extents of the response to nitrogen treatments in the two years; however, they responded to nitrogen treatments with the same trend. In addition, *Pn* and magnesium accumulation in the kernel were closely correlated with the pod yield among fertilizer treatments.

**Table 7.** Effects of calcium ($Ca_0$ and $Ca_1$: 568.0 kg CaO $ha^{-1}$) and nitrogen (0, 45, 90, 112.5, 135, and 157.5 kg N $ha^{-1}$) fertilizers' application on calcium accumulation and distribution in 2015 and 2016.

| Ca Fertilizer Level | N Fertilizer Level (kg N $ha^{-1}$) | 2015 | | | | | | 2016 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $A_V$ (g $Plant^{-1}$) | $AR_V$ (%) | $A_P$ (g $Plant^{-1}$) | $AR_P$ (%) | $A_K$ (g $Plant^{-1}$) | $AR_K$ (%) | $A_V$ (g $Plant^{-1}$) | $AR_V$ (%) | $A_P$ (g $Plant^{-1}$) | $AR_P$ (%) | $A_K$ (g $Plant^{-1}$) | $AR_K$ (%) |
| $Ca_0$ | 0 | 67.3 ± 1.5 e | 80.9 ± 0.5 a | 12.6 ± 0.4 e | 15.2 ± 0.7 a | 3.2 ± 0.3 d | 3.9 ± 0.2 bc | 218.9 ± 7.8 c | 84.7 ± 0.4 a | 29.2 ± 1.2 c | 11.3 ± 0.2 a | 10.3 ± 0.3 e | 4.0 ± 0.2 abc |
| | 45 | 93.6 ± 5.7 d | 80.7 ± 1.0 a | 17.1 ± 0.4 d | 14.9 ± 1.1 a | 5.1 ± 0.3 c | 4.4 ± 0.1 ab | 242.9 ± 7.2 c | 84.3 ± 0.5 a | 33.4 ± 0.7 bc | 11.6 ± 0.5 a | 11.9 ± 0.3 d | 4.1 ± 0.1 abc |
| | 90 | 113.9 ± 3.0 c | 81.1 ± 0.2 a | 20.3 ± 0.7 c | 14.5 ± 0.1 a | 6.3 ± 0.2 ab | 4.5 ± 0.1 a | 307.7 ± 5.6 b | 85.1 ± 0.1 a | 38.2 ± 0.4 ab | 10.6 ± 0.1 a | 15.6 ± 0.2 b | 4.3 ± 0.1 ab |
| | 112.5 | 123.3 ± 2.9 bc | 81.0 ± 0.4 a | 21.9 ± 0.1 b | 14.4 ± 0.2 a | 7.0 ± 0.2 a | 4.6 ± 0.2 a | 320.7 ± 12.2 ab | 85.3 ± 0.6 a | 38.7 ± 1.1 ab | 10.3 ± 0.5 a | 16.6 ± 0.3 a | 4.4 ± 0.2 a |
| | 135 | 129.2 ± 3.9 b | 81.3 ± 0.3 a | 23.7 ± 0.5 a | 14.9 ± 0.1 a | 6.1 ± 0.2 b | 3.8 ± 0.2 c | 328.9 ± 12.2 ab | 85.2 ± 0.3 a | 42.2 ± 0.8 a | 10.9 ± 0.3 a | 15.1 ± 0.2 bc | 3.9 ± 0.1 bc |
| | 157.5 | 141.9 ± 1.8 a | 82.3 ± 0.1 a | 24.7 ± 0.3 a | 14.3 ± 0.1 a | 5.7 ± 0.2 bc | 3.3 ± 0.1 c | 342.7 ± 6.8 a | 85.4 ± 0.5 a | 43.8 ± 3.4 a | 10.9 ± 0.7 a | 14.7 ± 0.6 c | 3.7 ± 0.2 c |
| $Ca_1$ | 0 | 126.7 ± 2.5 d | 85.2 ± 0.3 c | 17.6 ± 0.2 e | 11.8 ± 0.3 a | 4.4 ± 0.1 d | 3.0 ± 0.1 bc | 336.7 ± 8.8 c | 85.7 ± 0.2 b | 43.0 ± 0.9 b | 11.0 ± 0.1 a | 13.3 ± 0.3 d | 3.4 ± 0.1 b |
| | 45 | 183.5 ± 1.7 c | 85.6 ± 0.2 bc | 24.0 ± 0.7 d | 11.2 ± 0.2 ab | 6.9 ± 0.2 c | 3.2 ± 0.1 ab | 391.9 ± 12.7 b | 86.3 ± 0.1 b | 45.2 ± 1.3 ab | 10.0 ± 0.1 b | 17.0 ± 0.3 c | 3.7 ± 0.1 ab |
| | 90 | 222.0 ± 5.3 b | 86.0 ± 0.4 abc | 27.5 ± 0.6 c | 10.7 ± 0.4 b | 8.6 ± 0.2 b | 3.3 ± 0.1 a | 468.8 ± 7.1 a | 87.4 ± 0.3 a | 46.8 ± 2.9 ab | 8.7 ± 0.4 c | 21.1 ± 0.3 ab | 3.9 ± 0.1 a |
| | 112.5 | 239.6 ± 10.7 b | 86.3 ± 0.6 abc | 28.6 ± 0.3 c | 10.3 ± 0.4 b | 9.3 ± 0.1 a | 3.4 ± 0.2 a | 485.0 ± 12.5 a | 87.3 ± 0.3 a | 48.2 ± 0.8 ab | 8.7 ± 0.1 c | 22.6 ± 0.7 a | 4.1 ± 0.2 a |
| | 135 | 268.0 ± 7.7 a | 87.0 ± 0.6 a | 30.9 ± 1.3 b | 10.0 ± 0.6 b | 9.0 ± 0.2 ab | 2.9 ± 0.1 bc | 503.4 ± 19.4 a | 87.6 ± 0.3 a | 50.0 ± 2.7 a | 8.7 ± 0.4 c | 21.1 ± 0.7 ab | 3.7 ± 0.2 ab |
| | 157.5 | 278.1 ± 5.1 a | 87.0 ± 0.5 ab | 33.0 ± 1.1 a | 10.3 ± 0.5 b | 8.5 ± 0.2 b | 2.7 ± 0.1 c | 512.6 ± 11.4 a | 87.7 ± 0.3 a | 51.4 ± 1.6 a | 8.8 ± 0.2 c | 20.8 ± 0.5 b | 3.6 ± 0.1 ab |
| Significance of factors | | | | | | | | | | | | | |
| Ca | | ** | ** | ** | ** | ** | ** | ** | ** | ** | ** | ** | ** |
| N | | ** | * | ** | NS | ** | ** | ** | ** | ** | ** | ** | ** |
| Ca × N | | ** | NS | NS | NS | ** | NS | NS | NS | NS | NS | ** | NS |

$A_V$, $A_P$, and $A_K$ stand for the accumulation of nutrients in the vegetative organs, peg and husk, and kernel of the plant, respectively. $AR_V$, $AR_P$, and $AR_K$ stand for the allocation rate of nutrients in the vegetative organs, peg and husk, and kernel of the plant, respectively. Data are presented as mean ± SE, $n$ = 3. Values followed by different lowercase letters in the same column were significantly different among treatments at the 0.05 level for the same factor. Two-way analysis of variance was performed to evaluate the effects of calcium (Ca), nitrogen (N), and their interactions (Ca × N). NS means non-significant. * and ** indicate significant difference at $p < 0.05$ and $p < 0.01$ probability levels, respectively.

**Table 8.** Effects of calcium ($Ca_0$ and $Ca_1$: 568.0 kg CaO $ha^{-1}$) and nitrogen (0, 45, 90, 112.5, 135, and 157.5 kg N $ha^{-1}$) fertilizers' application on magnesium accumulation and distribution in 2015 and 2016.

| Ca Fertilizer Level | N Fertilizer Level (kg N $ha^{-1}$) | 2015 | | | | | | 2016 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $A_V$ (g $Plant^{-1}$) | $AR_V$ (%) | $A_P$ (g $Plant^{-1}$) | $AR_P$ (%) | $A_K$ (g $Plant^{-1}$) | $AR_K$ (%) | $A_V$ (g $Plant^{-1}$) | $AR_V$ (%) | $A_P$ (g $Plant^{-1}$) | $AR_P$ (%) | $A_K$ (g $Plant^{-1}$) | $AR_K$ (%) |
| $Ca_0$ | 0 | 55.0 ± 1.2 e | 74.5 ± 0.7 a | 11.3 ± 0.6 d | 15.3 ± 0.4 a | 7.6 ± 0.6 c | 10.3 ± 0.5 c | 80.2 ± 3.0 c | 73.9 ± 0.5 a | 12.9 ± 0.3 d | 12.0 ± 0.4 ab | 15.3 ± 0.3 e | 14.1 ± 0.2 c |
| | 45 | 80.2 ± 4.9 d | 75.2 ± 0.8 a | 13.1 ± 0.4 c | 12.4 ± 0.9 b | 13.3 ± 0.9 b | 12.4 ± 0.3 b | 94.1 ± 2.6 b | 71.0 ± 0.6 b | 14.7 ± 0.3 d | 11.1 ± 0.3 ab | 23.7 ± 0.5 d | 17.9 ± 0.3 ab |
| | 90 | 94.9 ± 2.5 c | 74.5 ± 0.3 a | 14.9 ± 0.5 b | 11.7 ± 0.1 b | 17.6 ± 0.5 a | 13.8 ± 0.4 a | 115.7 ± 2.2 a | 70.9 ± 0.2 b | 17.5 ± 0.1 c | 10.8 ± 0.1 b | 30.0 ± 0.3 c | 18.4 ± 0.2 a |
| | 112.5 | 99.8 ± 2.4 bc | 74.3 ± 0.7 a | 15.8 ± 0.1 b | 11.8 ± 0.2 b | 18.6 ± 0.5 a | 13.9 ± 0.5 a | 121.6 ± 4.8 a | 70.0 ± 1.1 b | 18.9 ± 0.7 bc | 10.9 ± 0.5 ab | 33.0 ± 0.5 a | 19.1 ± 0.7 a |
| | 135 | 107.1 ± 3.3 ab | 74.5 ± 0.7 a | 19.0 ± 0.2 a | 13.2 ± 0.4 b | 17.7 ± 0.5 a | 12.3 ± 0.4 b | 123.3 ± 4.7 a | 70.2 ± 0.6 b | 20.6 ± 0.5 ab | 11.8 ± 0.3 ab | 31.6 ± 0.5 b | 18.0 ± 0.4 ab |
| | 157.5 | 114.0 ± 1.4 a | 75.5 ± 0.3 a | 19.2 ± 0.3 a | 12.7 ± 0.1 b | 17.7 ± 0.3 a | 11.7 ± 0.3 b | 126.8 ± 2.7 a | 70.9 ± 0.1 b | 21.7 ± 1.0 a | 12.1 ± 0.3 a | 30.3 ± 0.4 c | 16.9 ± 0.4 b |
| $Ca_1$ | 0 | 43.9 ± 1.0 d | 69.4 ± 0.4 a | 10.8 ± 0.1 e | 17.0 ± 0.4 a | 8.6 ± 0.2 d | 13.6 ± 0.1 c | 85.9 ± 1.6 d | 71.5 ± 0.8 a | 14.9 ± 0.5 bc | 12.4 ± 0.2 a | 19.3 ± 0.9 d | 16.1 ± 0.7 b |
| | 45 | 63.6 ± 0.7 c | 69.3 ± 0.2 a | 12.2 ± 0.3 d | 13.3 ± 0.2 b | 16.0 ± 0.4 c | 17.4 ± 0.3 ab | 102.9 ± 2.8 c | 70.7 ± 0.2 a | 14.5 ± 0.5 c | 9.9 ± 0.1 b | 28.2 ± 0.5 c | 19.4 ± 0.2 a |
| | 90 | 76.6 ± 1.6 b | 68.6 ± 0.4 a | 15.0 ± 0.3 c | 13.4 ± 0.4 b | 20.1 ± 0.4 b | 18.0 ± 0.3 a | 127.4 ± 2.7 b | 70.9 ± 0.7 a | 17.1 ± 1.2 ab | 9.5 ± 0.6 b | 35.2 ± 0.5 b | 19.6 ± 0.5 a |
| | 112.5 | 80.8 ± 3.3 b | 68.4 ± 1.0 a | 15.1 ± 0.2 c | 12.8 ± 0.4 b | 22.1 ± 0.3 a | 18.8 ± 0.7 a | 136.5 ± 3.6 ab | 69.7 ± 0.7 a | 18.3 ± 0.3 a | 9.4 ± 0.1 b | 40.8 ± 0.8 a | 20.9 ± 0.7 a |
| | 135 | 90.9 ± 2.6 a | 69.8 ± 0.8 a | 16.6 ± 0.7 b | 12.8 ± 0.7 b | 22.6 ± 0.6 a | 17.4 ± 0.5 ab | 141.5 ± 5.4 a | 70.4 ± 0.5 a | 18.9 ± 1.1 a | 9.4 ± 0.4 b | 40.3 ± 0.5 a | 20.1 ± 0.6 a |
| | 157.5 | 95.1 ± 1.8 a | 70.5 ± 0.8 a | 17.7 ± 0.6 a | 13.2 ± 0.5 b | 22.1 ± 0.4 a | 16.4 ± 0.4 b | 147.5 ± 3.5 a | 71.6 ± 0.5 a | 19.3 ± 1.0 a | 9.4 ± 0.3 b | 39.2 ± 0.4 a | 19.0 ± 0.5 a |
| Significance of factors | | | | | | | | | | | | | |
| Ca | | ** | ** | ** | ** | ** | ** | ** | NS | NS | ** | ** | ** |
| N | | ** | NS | ** | ** | ** | ** | ** | ** | ** | ** | ** | ** |
| Ca × N | | NS | NS | * | NS | ** | NS | NS | NS | NS | ** | ** | NS |

$A_V$, $A_P$, and $A_K$ stand for the accumulation of nutrients in the vegetative organs, peg and husk, and kernel of the plant, respectively. $AR_V$, $AR_P$, and $AR_K$ stand for the allocation rate of nutrients in the vegetative organs, peg and husk, and kernel of the plant, respectively. Data are presented as mean ± SE, $n = 3$. Values followed by different lowercase letters in the same column were significantly different among treatments at the 0.05 level for the same factor. Two-way analysis of variance was performed to evaluate the effects of calcium (Ca), nitrogen (N), and their interactions (Ca × N). NS means non-significant. * and ** indicate significant difference at $p < 0.05$ and $p < 0.01$ probability levels, respectively.

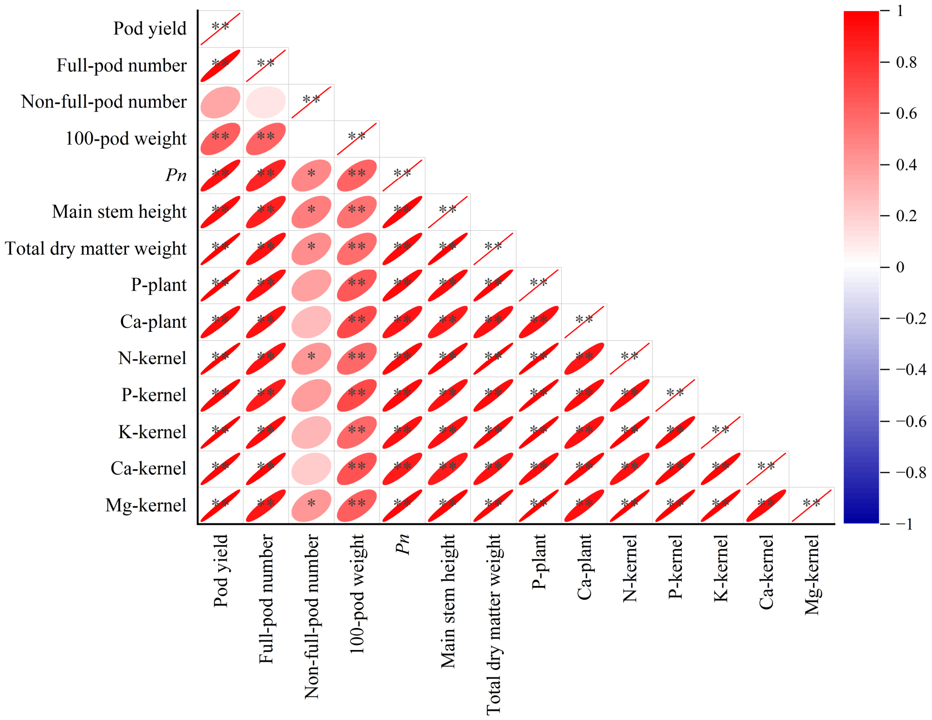


**Figure 4.** Pearson correlation analysis of pod yield and yield components (full-pod number, non-full-pod number, and 100-pod weight), net photosynthetic rate (*Pn*), the agronomic traits (main stem height), total dry matter weight, phosphorus and calcium accumulation in single plant (P-plant, Ca-plant), and nitrogen, phosphorus, potassium, calcium, and magnesium accumulation in the kernel (N-kernel, P-kernel, K-kernel, Ca-kernel, Mg-kernel) under nitrogen and calcium fertilizers' application. The depth of the color in each small square represents the degree of correlation between two indicators, and indicators that were positive and negative correlation are illustrated in red and blue, respectively. * and ** represent significant differences at $p < 0.05$ and $p < 0.01$ probability levels, respectively, and $n = 24$.

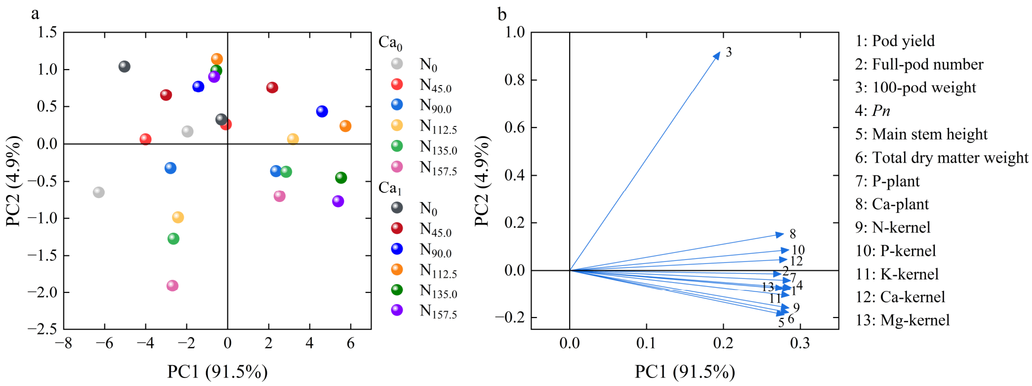


**Figure 5.** (**a**) The scores plot and (**b**) loadings plot of principal component analysis (PCA) based on the parameters of pod yield and yield components (full-pod number and 100-pod weight), net photosynthetic rate (*Pn*), the agronomic traits (main stem height), total dry matter weight, phosphorus and calcium accumulation in single plant (P-plant, Ca-plant), and nitrogen, phosphorus, potassium, calcium, and magnesium accumulation in the kernel (N-kernel, P-kernel, K-kernel, Ca-kernel, Mg-kernel) under calcium ($Ca_0$: 0 and $Ca_1$: 568 kg CaO·ha$^{-1}$) and nitrogen ($N_0$: 0, $N_{45.0}$: 45.0, $N_{90.0}$: 90.0, $N_{112.5}$: 112.5, $N_{135.0}$: 135.0, and $N_{157.5}$: 157.5 kg N ha$^{-1}$) fertilizers' application, and $n = 24$. Sample positions in the plane were delineated by PC1 and PC2, gathering 96.4% of the total variance.

### 3.7. Relationships between Fertilizers Application and Relative Yield

To quantify the effect of calcium and nitrogen fertilizer interactions on peanut yield, the best fit of the relationship between the fertilizers' application and the relative yield was obtained using a linear-plateau model (Figure 6). Without calcium fertilizer application, the minimum nitrogen fertilizer application able to provide the maximum relative yield (equal to 96.05%) was 94.61 kg $ha^{-1}$. After that, the relative yield increased linearly (with a slope equal to 0.567). Under 568 kg CaO $ha^{-1}$ of calcium fertilizer application, the minimum nitrogen fertilizer application capable of providing the maximum relative yield (equal to 98.99%) was 108.24 kg $ha^{-1}$. After that, the relative yield increased linearly (with a slope equal to 0.522).

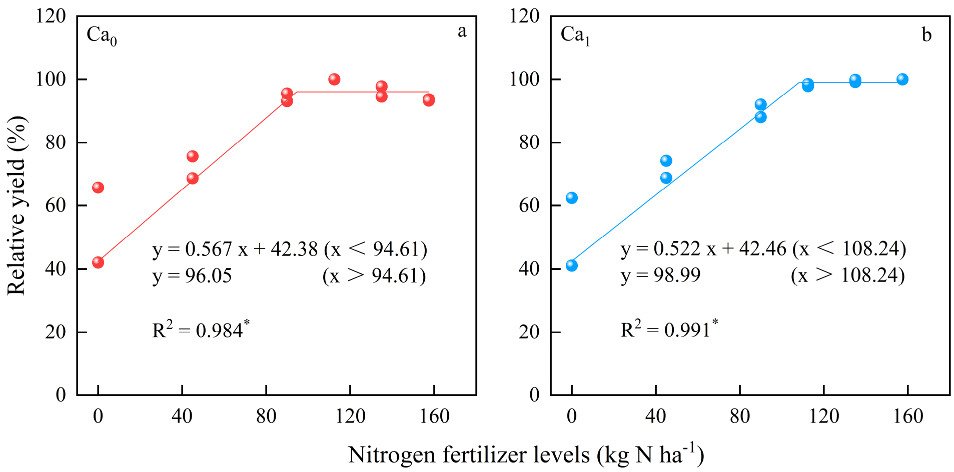


**Figure 6.** Relationship between nitrogen fertilizer levels and relative yield under (**a**) calcium ($Ca_0$: 0 kg CaO $ha^{-1}$) and (**b**) calcium ($Ca_1$: 568 kg CaO $ha^{-1}$) fertilizer application. * represents significant differences at $p < 0.05$ probability level.

## 4. Discussion

### 4.1. The Effects of Nitrogen and Calcium Application on Peanut Yield, Leaf Photosynthesis, Agronomic Traits, and Dry Matter Quality

Soil acidification caused by the long-term application of nitrogen fertilizer could dissolve crucial nutrients, such as potassium, calcium, and magnesium in the soil, resulting in soil impoverishment, aggravated soil-borne disease, and hindered crop growth [31,32]. Gypsum can be applied during the flowering stage to guarantee that there is enough calcium available in the fruiting zone to promote pod development, while calcium carbonate can also be utilized as a calcium source; it releases nutrients more slowly than gypsum because of its slower solubility [33]. In addition, other studies found that chemical amendments such as calcium oxide (CaO) were more effective at alleviating soil acidification [34,35]. This study demonstrated that applying 568 kg CaO $ha^{-1}$ ($Ca_1$) calcium fertilizer significantly promoted peanut pod yield by 11.5–25.8% and 14.7–29.6% in 2015 and 2016, respectively. The finding was consistent with a previous study [36], which concluded that calcium fertilizer application was required prior to the stage of peanut pod development to make sure that pods received enough calcium, which may result in a 20–30% increase in yield. $Ca_1$ significantly increased the number of full pods per plant and the 100-pod weight, indicating that the increased pod yield was due to a significant increase in these factors. This trend in yield was consistent with previous studies on calcium in various crops such as peanuts and fava beans [37,38]. Crops accumulate total biomass through photosynthesis and distribute photosynthetic products to the harvested organs, which form the crops' yields. Previous studies found that calcium application had a significant effect on leaf photosynthesis, agronomic traits, and dry matter accumulation [39,40]. This study found that $Ca_1$ treatment significantly increased the net photosynthetic rate of peanut leaves, improving the quality of the vegetative and reproductive organs as well as the whole plant. The results indicate that applying 568 kg CaO ha$^{-1}$ calcium fertilizer enhanced leaf photosynthesis, increased the plant stem height and dry matter accumulation, and increased the peanut pod yield.

The application of nitrogen fertilizer is crucial to achieve high crop yields. However, in another study, more nitrogen fertilizer was applied, frequently at rates much higher than those that crops can absorb, leading to the inefficient use of nitrogen fertilizer [41]. This study revealed that under 0 kg CaO ha$^{-1}$ treatment ($Ca_0$), pod yields increased steadily with nitrogen application rates of 0–112.5 kg ha$^{-1}$, peaking at 112.5 kg N ha$^{-1}$ ($N_{112.5}$), with a 52.3% and 138.0% increase in 2015 and 2016, respectively, compared to 0 kg N ha$^{-1}$ ($N_0$). However, excessive application of nitrogen (greater than $N_{112.5}$) did not affect or even reduced the pod yield, compared with that of $N_0$. This trend was consistent with the number of full pods per plant and the 100-pod weight, which first increased and then declined, peaking at $N_{112.5}$, as described by previous study [42]. This indicated that the pod yield of different peanut varieties increased initially and then decreased eventually by increasing nitrogen from 0 to 150 kg ha$^{-1}$; the efficiency was greatly different owing to the soil texture and nitrogen level. Excessive nitrogen reduced light transmittance and the net assimilation rate [42], led to soil pollution and the degradation of soil quality, and harmed sustainable soil development [43–45]. In this study, increasing nitrogen rates improved the dry matter quality, which was in line with the findings of previous research by Zhai et al. [46]. However, no significant difference in dry matter quality was found between the 135 and 157.5 kg N ha$^{-1}$ treatments, which suggested that excess nitrogen may not affect or may even reduce pod yields.

Calcium fertilizer is typically used in conjunction with nitrogen, phosphorus, and potassium fertilizers, as it affects growth and development, nutrient absorption and utilization, and yield and kernel quality [22,47]. This study has demonstrated that under calcium fertilizer conditions, the peanut pod yield gradually increased with the application of nitrogen fertilizer; however, the differences between applications of $N_{112.5}$, $N_{135.0}$, and $N_{157.5}$ were not significant. The number of full pods per plant and the 100-pod weight were highest under $N_{112.5}$ treatment. Furthermore, with calcium fertilization, the application of nitrogen fertilizer significantly increased the net photosynthetic rate, main stem height, and dry mass of peanut leaves. These indices were significantly positively correlated with the pod yield ($p < 0.01$), and the principal component analyses revealed that the net photosynthetic rate was closely correlated with pod yield among fertilizer treatments. Therefore, with the interaction of nitrogen and calcium, there is an improvement in the net photosynthetic rate and main stem height, promotion of dry matter accumulation in individual plants, and an increase in the number of full pods per plant and 100-pod weight, leading to an increase in pod yield.

### *4.2. The Effects of Nitrogen and Calcium Application on Nutrient Accumulation and Distribution*

The absorption of nutrients is critical for plant growth and biomass accumulation; it is essential to achieve high yields and quality in peanut crops. Peanuts are a calcium-demanding crop that requires a significant amount of calcium for pod enlargement and enrichment. However, Xing et al. [48] discovered that both calcium deficiency and excess calcium inhibited nitrogen absorption and utilization, and the adverse effects of calcium deficiency on seedling growth and nitrogen metabolism were greater than the adverse effects of excess $Ca^{2+}$ supply. According to Shi et al. [49], the application of exogenous calcium could enhance nutrient absorption and accumulation in different organs of peanut plants under salt stress and promote the distribution ratio of nitrogen, phosphorus, and potassium in mature pods of peanut plants. In this study, we estimated the accumulation and distribution of nutrients in the various organs of peanuts plants and found that the application of 568 kg CaO ha$^{-1}$ of calcium fertilizer enhanced the accumulation of nitrogen, phosphorus, and calcium in the whole plant and promoted the accumulation of nitrogen, phosphorus, potassium, calcium, and magnesium in the kernel. However, with the application of calcium, the distribution of nitrogen, phosphorus, and potassium in the vegetative and reproductive organs decreased, while their distribution in the kernel increased. The distribution of calcium in the reproductive organs and kernels decreased, while its distribution in the vegetative organs increased. Therefore, calcium application affected the absorption and distribution of nutrients in each organ and in the whole plant, promoted the accumulation of each nutrient element in the kernel, and impacted the yield and quality of peanuts. However, a study on lettuce by Bezerra, Marques, Bardiviesso, et al. [50] found that the application of calcium did not affect the accumulation of nutrients. The discrepancy in these results might be due to differences in the amount and method of calcium application.

Nitrogen is an essential structural component of plants; it plays a pivotal role in stem and leaf growth, fruit development, and crop yield. This study demonstrated that the absence of calcium significantly increased the accumulation of nitrogen, potassium, calcium, and magnesium in the whole plant, whereas the accumulation of phosphorus initially increased and then subsequently decreased, peaking at the $N_{112.5}$ treatment. The accumulation of nutrients across various organs indicated that nitrogen accumulation only significantly increased with the $N_0$ and 45 kg N $ha^{-1}$ ($N_{45}$) treatments, whereas the accumulation of potassium, calcium, and magnesium in the vegetative organs, peg, and husk increased significantly. Moreover, the accumulation of phosphorus, potassium, calcium, and magnesium initially increased and then decreased, with the peak accumulation observed at the $N_{112.5}$ treatment. Nevertheless, the distribution of nutrients in each organ demonstrated less variation with nitrogen application, indicating that the application of nitrogen (less than $N_{112.5}$) affected the absorption of nutrients in each organ and in the whole plant, improved the accumulation of each nutrient in the kernel, and impacted the pod yield and the quality of the peanuts. These findings were consistent with a previous study [51], which reported an increase in sesame seed yield, plant height, stem diameter, auxiliary branch number per plant, and capsule length following an increase in nitrogen from 0 to 200 kg $ha^{-1}$.

The accumulation and distribution of nutrients in the whole plant were significantly affected by the reduction in nitrogen and the increase in calcium. Under the conditions of calcium fertilizer, as the nitrogen application rate increased, the accumulation of nitrogen, phosphorus, potassium, calcium, and magnesium first increased and then decreased, reaching its maximum at the application rate of 112.5 kg $ha^{-1}$. Moreover, these nutrients were significantly positively correlated with the pod yield ($p < 0.01$), indicating that the combined application of 112.5 kg $ha^{-1}$ nitrogen and 568 kg $ha^{-1}$ calcium fertilizers could enhance the accumulation of nutrients in the kernel, which would increase the pod yield. The results were consistent with a previous report [52], which demonstrated the significant influence of the foliar application of organic liquid fertilizers fortified with phosphorus and calcium on the tomato yield and fruit quality. Meanwhile, a linear-plateau dependency was observed between the relative yield and fertilizer application, which revealed that with simulated nitrogen fertilizer levels above 108 kg $ha^{-1}$, the relative yield value was relatively high at $Ca_1$. The suitable nitrogen treatment (112.5 kg $ha^{-1}$) in this study was close to the estimated value when applying 568 kg $ha^{-1}$ calcium fertilizer. Therefore, applying 568 kg $ha^{-1}$ calcium fertilizer while reducing the amount of nitrogen fertilizer to 112.5 kg $ha^{-1}$ is an important cultivation strategy that can help maintain peanut yields in acidic red soil and maximize the effect of nitrogen fertilizer.

## 5. Conclusions

The addition of calcium and nitrogen fertilizers to calcium-deficient acidic red soil significantly influenced peanut yield, as well as the yield components, *Pn*, main stem height, dry matter, and nutrient accumulation. There was a highly significant positive correlation between pod yield and these indicators. With the same calcium fertilizer level, the addition of nitrogen fertilizer significantly increased the main stem height and *Pn* and enhanced the accumulation of dry matter and nutrients in the plant, particularly in the kernel. Similarly, under the same amounts of nitrogen fertilizer, the addition of calcium notably increased *Pn* and facilitated the accumulation of dry matter, calcium, and magnesium. The pod yield gradually increased with an increasing nitrogen application rate (0–112.5 kg ha$^{-1}$); the yield peaked at the $N_{112.5}$ treatment, with an increase of 52.3–138.0% compared to that of $N_0$. However, excessive nitrogen (N > 112.5 kg ha$^{-1}$) resulted in a decreased pod yield. Under different nitrogen fertilizer levels, the addition of calcium increased peanut pod yields by 11.5–29.6% by promoting *Pn*, nutrient uptake, and accumulation in individual plants, as well as nutrient accumulation in the kernel. Therefore, this study recommends applying 112.5 kg ha$^{-1}$ of nitrogen fertilizer and 568 kg ha$^{-1}$ of calcium fertilizer in calcium-deficient acidic red soil, reducing nitrogen fertilizer by 28.6% compared to the traditional fertilization quantity of 157.5 kg ha$^{-1}$. These results demonstrated that it was possible to improve the nutritional value of peanuts and provide a theoretical foundation for synergistic cultivation technology in peanut production.

**Author Contributions:** Conceptualization, S.W. and L.L.; data curation, J.W., J.Z. (Jialei Zhang), Y.G. and J.Z. (Jie Zou); methodology, F.G. and S.Y.; formal analysis, J.W. and J.Z. (Jie Zou); writing—original draft, J.W., Y.G. and J.Z. (Jie Zou); writing—review and editing, J.W. and J.Z. (Jie Zou); funding acquisition, L.L. and S.W. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the Key R&D Program of Shandong Province, China (2021LZGC026); the Major Science and Technology Innovation Project of Shandong Province, China (2022CXPT031); and the National Modern Agricultural Industrial Technology System Funding Project (CARS-13).

**Data Availability Statement:** The data presented in this study are available within the article.

**Acknowledgments:** This work was supported by Yunyuan Experimental Station, modern agricultural science and technology demonstration park, Hunan Agricultural University, Changsha, China.

**Conflicts of Interest:** The authors declare no conflict of interest.

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