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Optimizing Tomato Cultivation: Impact of Ammonium–Nitrate Ratios on Growth, Nutrient Uptake, and Fertilizer Utilization

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Abstract: Tomatoes, an essential crop in controlled environments, benefit significantly from the careful use of nitrogen fertilizers, which are crucial for improving both yield and nitrogen efficiency. Using a tomato pot experiment arranged in a facility greenhouse, five treatments were established as follows: a control excluding the application of nitrogen fertilizer (C), and applications of ammonium nitrogen and nitrate nitrogen with nitrogen mass ratios of 0:100 (A_0N_{100}), 25:75 ($A_{25}N_{75}$), 50:50 ($A_{50}N_{50}$), 75:25 ($A_{75}N_{25}$), and 100:0 ($A_{100}N_0$), to study the effects of different ratios of nitrogen mass on tomato yield, quality, nutrient accumulation, and nitrogen fertilizer utilization. The results showed that compared with C, the different ammonium–nitrate ratios significantly increased the yield, dry matter mass, N, P, and K accumulation, soluble solids, soluble sugars, and vitamin C content (Vc) of the tomatoes. Among all the treatments, $A_{75}N_{25}$ tomatoes had the highest dry matter accumulation, nitrogen, phosphorus, and potassium accumulation in fruits, soluble sugar, and soluble solids content. The differences in tomato yield and nitrogen fertilizer utilization between $A_{75}N_{25}$ and $A_{100}N_0$ were insignificant but their values were significantly higher than those of the other treatments. $A_{75}N_{25}$ had the highest nitrogen fertilizer utilization rate, 42.1% to 82.3% higher than C, $A_{25}N_{75}$, and $A_{50}N_{50}$. Hence, an ammonium-to-nitrate nitrogen mass ratio of 75:25 optimized tomato yield and quality in a controlled environment while minimizing nutrient loss.

Keywords: tomato; ammonium nitrogen; nitrate nitrogen; yield; quality

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1. Introduction

Tomatoes are a significant crop for facility cultivation due to their high nutritional value, minimal environmental requirements, simple cultivation process, and superior yield and quality compared with outdoor-grown tomatoes. Consequently, facility-grown tomatoes have become the predominant crop in Chinese agricultural facilities [1,2].

As highlighted in previous studies [3], nitrogen is indispensable for achieving optimal agricultural yields. This essential nutrient is fundamental for forming vital organic molecules within plants, including proteins, nucleic acids, and chlorophyll. Its significant contribution to synthesizing these compounds underscores its pivotal influence on plant development and productivity [4]. This study aims to address the issue of inefficient nitrogen fertilizer use, where overapplication by farmers leads to economic inefficiency and environmental concerns. The problem investigated is that of determining an optimal ammonium–nitrate nitrogen ratio that enhances tomato yield and quality while minimizing nutrient loss. Unfortunately, only a fraction of these fertilizers are assimilated by the plants. Recent studies [5,6] have shown that mixed nitrogen forms can significantly improve plant growth and yield compared with single nitrogen sources. However, there remains a gap in

understanding the specific impacts of varying ammonium-to-nitrate ratios in controlled environments, particularly for tomato cultivation. The unabsorbed portion not only results in economic inefficiency and resource wastage but also contributes to environmental concerns such as air and water pollution, soil fertility decline, and biodiversity reduction, as highlighted by researchers [7]. Consequently, adopting a scientific and considered approach to fertilization emerges as a crucial strategy for enhancing both the yield and quality of crops like tomatoes, alongside bolstering both economic gains and ecological sustainability. Our study compared a range of ammonium-to-nitrate ratios, including $A_{100}N_0$ (100% ammonium nitrogen), to comprehensively evaluate the effects of different nitrogen forms on tomato growth and yield. While high concentrations of ammonium nitrogen are known to potentially cause toxic effects, understanding these effects in a controlled experimental setup allows more detailed analysis of the optimal nitrogen balance for tomato cultivation.

The efficiency with which plants absorb and distribute nitrogen is mainly contingent on the specific forms of nitrogen available, with plants exhibiting preferences and biases towards certain nitrogenous compounds during nutrient uptake. Maintaining optimal ratios of ammonium to nitrate nitrogen can significantly enhance plant growth, development, yield, and product quality, a point underscored previously [8]. For instance, studies [9,10] demonstrated that N treatments are more effective than A in promoting biomass accumulation in crops such as wheat and maize. Conversely, ammonium nitrogen tends to support the growth of aboveground plant structures in rice, whereas nitrate nitrogen more beneficially impacts the plant's belowground development [11]. Existing studies have shown that most of the nitrogen absorbed and utilized by plants is in the form of ammonium nitrogen (NH_4^+-N) and nitrate nitrogen (NO_3^--N), which have different effects on plant growth due to the differences in molecular structure between the two [12]. Studies have shown that most plants benefit more from a mixture of NH_4^+-N and NO_3^--N than from a single application of NH_4^+-N or NO_3^--N [13]. A single N source may limit crop growth, so a reasonable A ratio can improve crop tolerance to abiotic stresses and promote crop growth [4]. When ammonium nitrogen is the primary nitrogen source, crop biomass decreases, leading to the degradation of leaf physiological functions [14]. Ref. [15] showed that the ammonium or nitrate nitrogen supply alone harms tomatoes' high quality and yield. When NH_4^+-N is over-represented in the nitrogen form ratio, plant uptake of anions is promoted, uptake of cations is inhibited, and toxic effects occur. When NO_3^--N accounts for a more significant proportion of the nitrogen form ratio, it encourages the uptake of cations by plants. It increases the osmotic potential of cells, which is favorable to plant growth, nitrogen uptake, and metabolism [16]. Researchers [17] investigated the effects of different ammonium–nitrate ratios on the yield and quality of melons. They concluded that ammonium–nitrate ratios of 50:50 or 25:75 significantly increased the soluble solids, titratable acid, vitamin C content, and yield of melons [18]. The 25:75 ratio of ammonium nitrogen to nitrate nitrogen increased the yield of chili peppers, promoted the accumulation of crop nutrients, and improved the utilization rate of nitrogen fertilizer in an experimental study of chili peppers in pots. Research [19] has shown that supply of ammonium nitrogen or nitrate nitrogen alone is not conducive to high quality and high yield of tomatoes, and the ratio of amide nitrogen and nitrate nitrogen needs to be optimized according to soil pH to achieve high quality and high yield of tomatoes. Studies have shown that ammonium and nitrate N ratios affect nutrient accumulation and fruit quality in open-air tomatoes [20]. Still, the analysis of ammonium and nitrate N ratios and their effects on tomatoes' growth, quality, and yield in facilities could be more precise.

Therefore, in this study, different A and N ratios were set up in a pot experiment in a facility greenhouse to study the effects of different A ratios on tomato yield, nutrient accumulation, and nitrogen fertilizer utilization to provide a reasonable theoretical basis for fertilizer application in greenhouse facility tomato production.

2. Materials and Methods

2.1. Experimental Materials

The experiment was conducted from July to December 2022 in the facility greenhouse of Gangji Agro-ecological Experimental Demonstration Base, Anhui Academy of Agricultural Sciences. Soil samples were collected from the top 20 cm of the greenhouse substrate, air-dried, and sieved through a 2 mm mesh, and 5.0 kg of this soil was placed into 8 L plastic pots. The initial physicochemical properties of the soil, including pH (6.8) and electrical conductivity (0.15 dS/m), were determined before the start of the experiment. The soil's textural class was sandy loam. The basic physicochemical properties of the soil were as follows: 0.27 g kg^{-1} of total nitrogen, 7.23 mg kg^{-1} of quick-acting phosphorus, 50.23 mg kg^{-1} of quick-acting potassium, and 11.65 g kg^{-1} of organic matter. The tomato variety used was Wanza 20, selected by the Horticulture Institute of Anhui Academy of Agricultural Sciences. The fertilizers used were analytically pure reagents; ammonium and nitrate nitrogen fertilizers were $(NH_4)_2SO_4$ and $Ca(NO_3)_2$, phosphorus fertilizer was KH_2PO_4, and potassium fertilizers were KH_2PO_4 and K_2SO_4, respectively.

2.2. Experimental Design

The nitrogen mass ratios were selected based on previous studies indicating that a mixture of ammonium and nitrate nitrogen can improve nutrient uptake and plant growth. The ratios 0:100, 25:75, 50:50, 75:25, and 100:0 were chosen to cover a wide range of potential combinations to identify the most effective ratio for tomato growth (Table 1):

- C: No nitrogen fertilizer treatment;
- A_0N_{100}: Nitrogen mass ratio of ammonium nitrogen and nitrate nitrogen 0:100;
- $A_{25}N_{75}$: Nitrogen mass ratio of ammonium nitrogen and nitrate nitrogen 25:75;
- $A_{50}N_{50}$: Nitrogen mass ratio of ammonium nitrogen and nitrate nitrogen 50:50;
- $A_{75}N_{25}$: Nitrogen mass ratio of ammonium nitrogen and nitrate nitrogen 75:25;
- $A_{100}N_0$: Nitrogen mass ratio of ammonium nitrogen and nitrate nitrogen 100:0.

Each treatment involved the same nitrogen dose of 1600 mg kg^{-1} of dry soil, divided into four equal applications. Phosphorus and potassium fertilizer doses were the same for all treatments, applied at 840 mg kg^{-1} and 1800 mg kg^{-1}, respectively, using the same method as for nitrogen fertilizer. Seedlings were raised in hole trays in the facility greenhouse for 40 days and then moved into pots on 10 August 2022, with one plant per pot. The basal fertilizer was applied before tomato transplanting, with three subsequent applications on 25 August, 5 September (flowering stage), and 30 September (early fruiting stage). All soil samples were homogenized to minimize potential biases, and plants were rotated periodically within the greenhouse to ensure uniform environmental conditions. Additionally, random sampling was used to analyze plants to avoid selection bias.

Table 1. Amount of fertilizer applied to different treatments (mg kg^{-1}).

Fertilizer	Base Fertilizer	Additional Fertilizer 1	Additional Fertilizer 2	Additional Fertilizer 3
N	600	300	400	300
P_2O_5	340	200	150	150
K_2O	700	300	500	300

2.3. Sample Collection and Processing

Tomatoes were sampled from the early flowering stage on 7 September, then every other month for the early, mid, and late fruiting stages [21,22]. Three pots were taken as three replicates for each sampling. Fresh samples were measured for plant height and stem thickness, then separated into leaves and stems (fruits) and weighed separately [23,24]. The fresh samples were dried at 105 °C for 30 min, followed by 75 °C for 48 h, then weighed for dry weights [25,26]. The dried samples were pulverized with an ultra-high-speed pulverized and digested in H_2SO_4-H_2O_2. Nitrogen, phosphorus, and potassium nutrients

in the samples were measured via Kjeldahl nitrogen fixation, the molybdenum antimony colorimetric method, and flame spectrophotometric method, respectively [27]. Fresh fruit was weighed separately for each yield, counting treatment at fruit ripening to calculate the yield [28]. Afterward, three tomatoes of uniform fruit size and maturity were randomly selected from each treatment, and the juice was extracted directly from the tomatoes using a hand-held refractometer to determine soluble solids; organic acids were determined via NaOH titration, Vc was determined via the 2,4-dichloroindophenol method and soluble sugars were determined via the anthrone method [29].

2.4. Data Processing and Analysis

Data quality was ensured via calibrating all measurement instruments before use, conducting duplicate measurements, and implementing strict protocols for soil and plant sample collection and processing.

$$\text{Nitrogen (N) accumulation on} = \text{N concentration} \times \text{dry matter mass}$$

$$\text{Phosphorus } (P_2O_5) \text{ accumulation} = P_2O_5 \text{ concentration} \times \text{dry matter mass}$$

$$\text{Potassium } (K_2O) \text{ accumulation} = K_2O \text{ concentration} \times \text{dry matter mass}$$

$$\text{Potassium } (K_2O) \text{ harvest index} = \frac{\text{fruit } K_2O \text{ accumulation}}{(\text{leaf} + \text{stem} + \text{fruit})\ K_2O \text{ accumulation}}$$

$$\text{NUE} = (\text{nitrogen uptake in treatment / nitrogen applied}) \times 100$$

Statistical analyses were conducted using ANOVA to assess the significance of differences between treatments. Assumptions of normality and homogeneity of variance were checked using the Shapiro–Wilk and Levene's tests, respectively. Post hoc comparisons were performed using Duncan's multiple-range test.

3. Results

3.1. Growth Traits

The number of fruits, single fruit weight, and yield differed significantly among treatments with different ammonium–nitrate ratios (Table 2, $p < 0.05$). The number of tomato fruit sittings and yield of all treatments showed an increasing and then decreasing trend with the increase of ammonium nitrogen ratio. The $A_{75}N_{25}$ tomatoes had the highest number of fruit sittings, single fruit weight, and yield, but the differences in the number of tomato fruit sittings, single fruit weight, and yield were insignificant with $A_{100}N_0$ ($p > 0.05$). The number of tomato fruit sittings, single fruit weight, and yield of $A_{75}N_{25}$ tomatoes were increased by 10~451%, 63~205%, and 82~1406% compared with those of C, A_0N_{100}, $A_{25}N_{75}$, and $A_{50}N_{50}$, respectively. This showed that an appropriate increase in the proportion of ammonium nitrogen fertilizer was beneficial to improve tomato yield.

Table 2. Tomato yield at different ammonium–nitrate ratios.

Characteristics	C	A_0N_{100}	$A_{25}N_{75}$	$A_{50}N_{50}$	$A_{100}N_0$
Number of fruit sets	1.33 ± 0.58 b	1.67 ± 0.58 b	2.67 ± 0.58 b	6.67 ± 1.15 a	7.33 ± 0.58 a
Single fruit weight (g)	14.74 ± 5.63 c	21.58 ± 3.39 b	24.17 ± 1.45 b	27.51 ± 3.95 b	44.97 ± 3.73 a
Yield (g plot^{-1})	21.81 ± 17.83 c	34.7 ± 8.19 c	64.82 ± 16.55 c	180.35 ± 3.24 b	328.51 ± 12.39 a

Note: Different lowercase letters in the same column indicate significant differences ($p < 0.05$). Results mean ± standard deviation ($n = 3$). Same below.

3.2. Yield

The effects of different ammonium–nitrate ratios on the plant height and stem thickness of tomatoes varied according to the harvest period (Table 3). At anthesis, the plant height of the tomato did not differ significantly among treatments ($p > 0.05$), and the stem thickness of $A_{100}N_0$ was considerably broader than other treatments ($p < 0.05$). At the

beginning, middle, and end of fruiting, $A_{100}N_0$ and $A_{75}N_{25}$ plant height and stem thickness did not differ significantly ($p < 0.05$), but they were all significantly higher than C and A_0N_{100} ($p < 0.05$).

Table 3. Tomato plant height and stem thickness under different ammonium–nitrogen ratios.

Characteristics	C	A_0N_{100}	$A_{25}N_{75}$	$A_{50}N_{50}$	$A_{75}N_{25}$	$A_{100}N_0$
Anthesis						
Plant height (cm)	30.97 ± 1.78 a	26.91 ± 5.56 a	27.64 ± 1.87 a	27.08 ± 5.08 a	27.76 ± 3.49 a	31.05 ± 3.06 a
Stem thickness (mm)	4.01 ± 0.05 b	4.02 ± 0.17 b	4.10 ± 0.41 b	3.90 ± 0.21 b	4.07 ± 0.18 b	4.51 ± 0.02 a
Early Fruiting Stage						
Plant height (cm)	48.06 ± 3.99 c	46.24 ± 4.23 c	51.14 ± 1.43 bc	55.93 ± 7.36 ab	58.09 ± 3.09 ab	61.02 ± 1.99 a
Stem thickness (mm)	4.71 ± 0.22 bc	4.22 ± 0.08 c	4.79 ± 0.38 b	4.82 ± 0.53 b	5.21 ± 0.1 a	5.61 ± 0.1 a
Mid-term Fruiting Stage						
Plant height (cm)	54.33 ± 2.68 bc	48.30 ± 5.12 c	59.70 ± 5.57 ab	65.26 ± 9.49 ab	65.28 ± 1.68 ab	70.04 ± 8.02 a
Stem thickness (mm)	4.71 ± 0.1 c	4.3 ± 0.1 c	4.65 ± 0.26 bc	5.12 ± 0.34 b	5.51 ± 0.15 ab	5.79 ± 0.28 a
End of Fruiting Stage						
Plant height (cm)	52.20 ± 7.89 b	50.27 ± 8.95 b	61.10 ± 6.38 ab	63.17 ± 13.50 ab	79.93 ± 10.26 a	70.23 ± 13.02 a
Stem thickness (mm)	5.02 ± 0.3 b	4.46 ± 0.52 b	5.15 ± 0.07 ab	5.34 ± 0.31 ab	5.71 ± 0.37 a	5.65 ± 0.69 a

Noted: Values followed by different lowercase letters (a, b, and c) within the same row are significantly different at $p < 0.05$ according to Duncan's Multiple Range Test.

3.3. Quality

Titratable acid, soluble sugar, soluble solids, Vc, and sugar–acid ratio were important qualities affecting the flavor quality of tomatoes. The titratable acid, soluble sugar, soluble solids content, and Vc content of tomato fruits in all treatments with the increase of ammonium nitrogen ratio showed an increasing and then decreasing trend. $A_{75}N_{25}$ fruits had the highest titratable acid–soluble sugar, sugar–acid ratio, soluble solids, Vc content, and sugar–acid ratio, but the titratable acid Vc content and sugar–acid ratio of tomato fruits among the nitrogen fertilizer treatments were not significantly different ($p > 0.05$). The soluble sugar and Vc content of $A_{75}N_{25}$ fruits were significantly higher than other treatment (Table 4).

Table 4. Effect of different ammonium–nitrate ratios on tomato quality.

Characteristics	C	A_0N_{100}	$A_{25}N_{75}$	$A_{50}N_{50}$	$A_{75}N_{25}$	$A_{100}N_0$
Titratable acid (%)	0.19 ± 0.01 b	0.24 ± 0.01 ab	0.26 ± 0.02 a	0.26 ± 0.01 a	0.27 ± 0.05 a	0.25 ± 0.02 a
Soluble sugar (%)	2.49 ± 0.02 f	3.2 ± 0.02 d	3.45 ± 0.04 c	3.44 ± 0.04 c	3.68 ± 0.03 a	3.53 ± 0.08 b
Soluble solids (%)	5.64 ± 0.1 d	6.31 ± 0.04 c	6.4 ± 0.03 b	6.28 ± 0.03 c	6.5 ± 0.01 a	6.47 ± 0.03 ab
Vitamin C (Vc) (mg 100 g^{-1})	21.11 ± 0.51 b	23.56 ± 0.02 a	23.55 ± 0.04 a	23.56 ± 0.04 a	23.66 ± 0.04 a	23.56 ± 0.02 a
Sugar–acid ratio	12.89 ± 0.67 b	13.56 ± 0.66 ab	13.12 ± 0.71 b	13.44 ± 0.7 ab	13.95 ± 2.68 a	13.94 ± 0.99 a

Noted: Values followed by different lowercase letters (a, b, c, d, and f) within the same row are significantly different at $p < 0.05$ according to Duncan's Multiple Range Test.

3.4. Dry Matter Accumulation

Aboveground dry matter mass increased gradually with growth and development in all treatments (Figure 1). At the flowering stage, the dry matter mass of tomato stems and leaves was small, and the differences in the stems' and leaves' dry matter mass were not significant under different treatments ($p > 0.05$) (Table 3). At the early stage of fruiting, the differences in the stems' and leaves' dry matter mass of $A_{50}N_{50}$, $A_{75}N_{25}$, and A100N0 were not significant, but the stems' dry matter mass was significantly higher than that of C, A_0N_{100}, $A_{25}N_{75}$ ($p < 0.05$). In the middle of the fruiting stage, the $A_{75}N_{25}$ tomato stems' and leaves' dry matter quality was the highest, and the stems' dry matter quality was

significantly higher than C, A_0N_{100}, or $A_{25}N_{75}$ ($p < 0.05$). At the end of the fruiting stage, $A_{75}N_{25}$ tomato stems', leaves', and fruits' dry matter mass accumulated highest, and the fruits' and stems' dry matter mass was significantly higher than other treatments ($p < 0.05$).

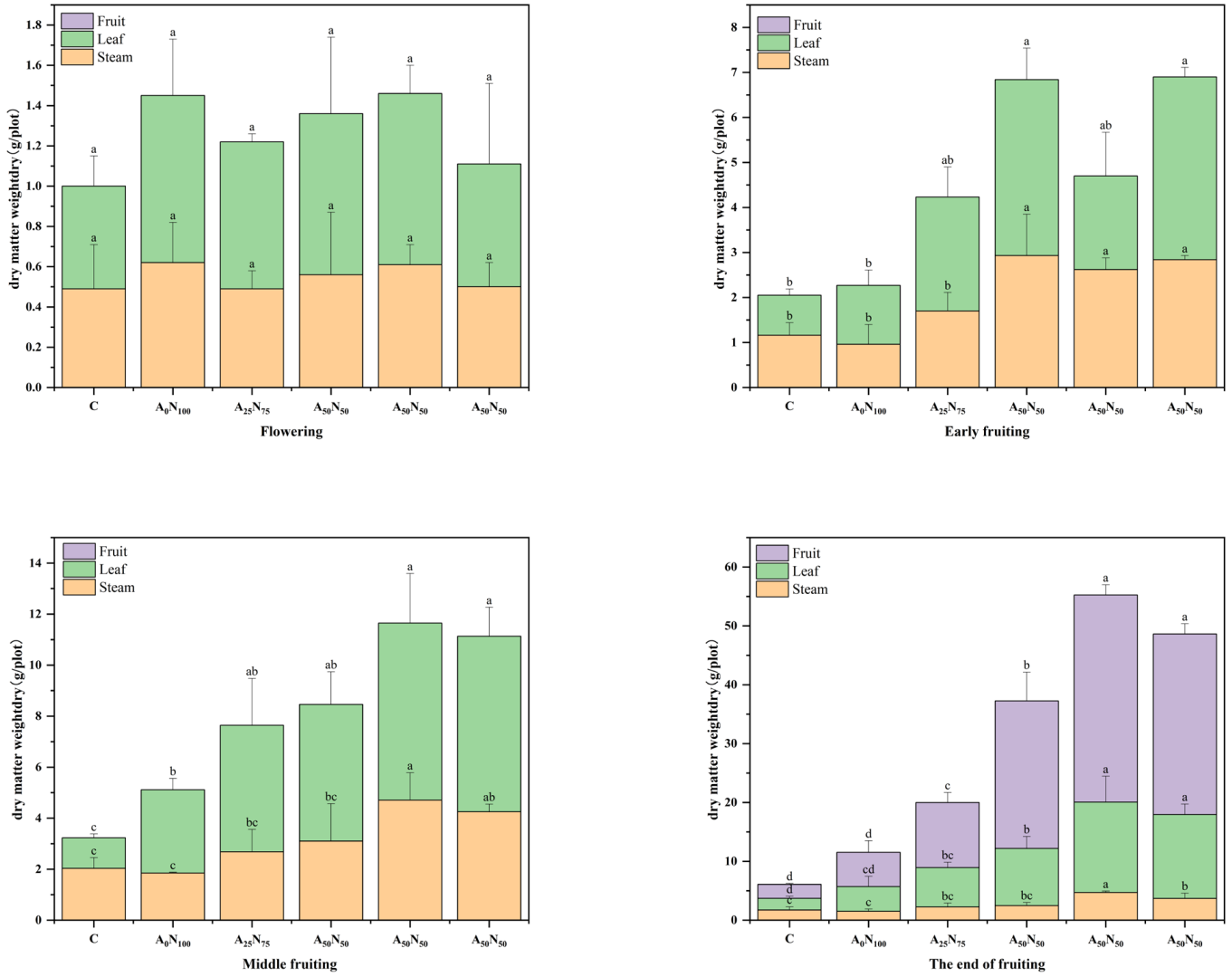


Figure 1. Dry matter accumulation of tomatoes under different ammonium–nitrate nitrogen ratios. Results are mean ± standard deviation (n = 3) and values followed by different lowercase letters (a, b, c, and d) within the same row are significantly different at $p < 0.05$ according to Duncan's Multiple Range Test.

3.5. Nutrient Accumulation

Nitrogen accumulation in tomato leaves and stems under different treatments gradually increased from flowering to the early fruiting stage and showed various degrees of decrease in nitrogen accumulation at the end of the fruiting stage, with the most significant reduction in C (Figure 2). At the end of the fruiting stage, more than 50% of the nitrogen was accumulated in fruits. At this time, $A_{75}N_{25}$ had the highest nitrogen accumulation in leaves, stems, and fruits, with fruit nitrogen accumulation significantly higher than the other treatments ($p < 0.05$).

Leaf phosphorus accumulation was higher than stem phosphorus accumulation in all treatments at the anthesis and early fruiting stage. At the end of the fruiting stage, phosphorus accumulation showed as fruit > stem > leaf (Figure 3). $A_{100}N_0$ leaf phosphorus accumulation at anthesis and stem phosphorus accumulation at the beginning of the

fruiting stage were significantly the same as those of the other treatments at the same sites. At the end of the fruiting stage, stem, leaf, and fruit phosphorus accumulation were still higher, but $A_{75}N_{25}$ fruit phosphorus accumulation was the highest, significantly higher than $A_{100}N_0$ and other treatments ($p < 0.05$).

Potassium accumulation was higher than nitrogen and phosphorus accumulation in all organs of the tomato (Figure 4). Stem potassium accumulation was higher than leaf potassium accumulation at the flowering and early fruiting stages. At the end of the fruiting stage, leaf and stem potassium accumulation decreased, and fruit potassium accumulation was significantly higher than stem and leaf potassium accumulation. At the end of fruiting, $A_{75}N_{25}$ stem and fruit potassium accumulation was substantially higher than other treatments ($p < 0.05$).

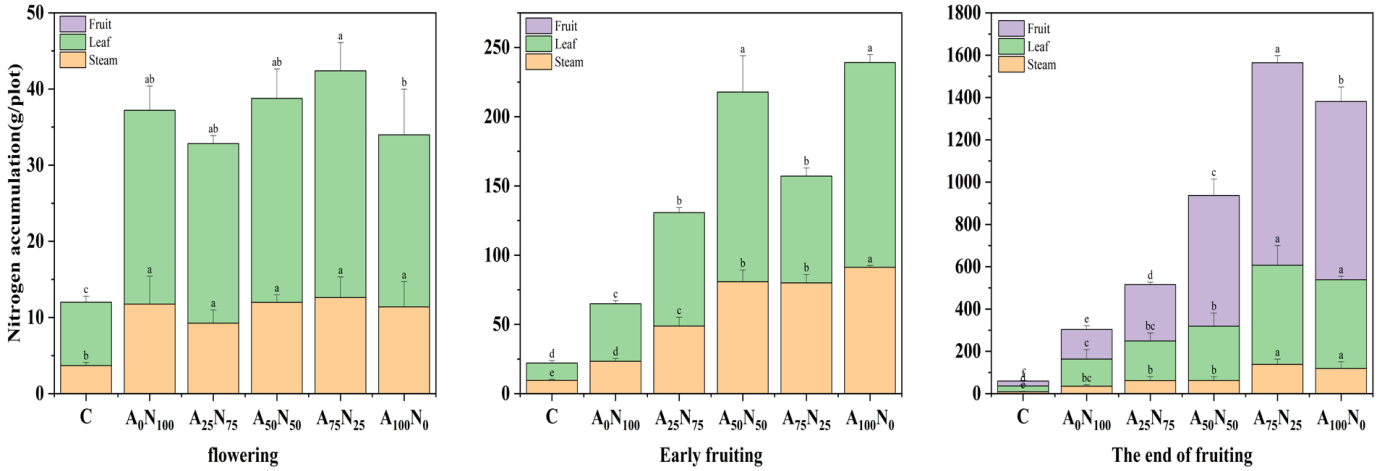


Figure 2. Nitrogen accumulation in tomatoes under different ammonium–nitrate nitrogen ratios. Note: Results are mean ± standard deviation (n = 3) and values followed by different lowercase letters (a, b, c, d, e, and f) within the same row are significantly different at $p < 0.05$ according to Duncan's Multiple Range Test.

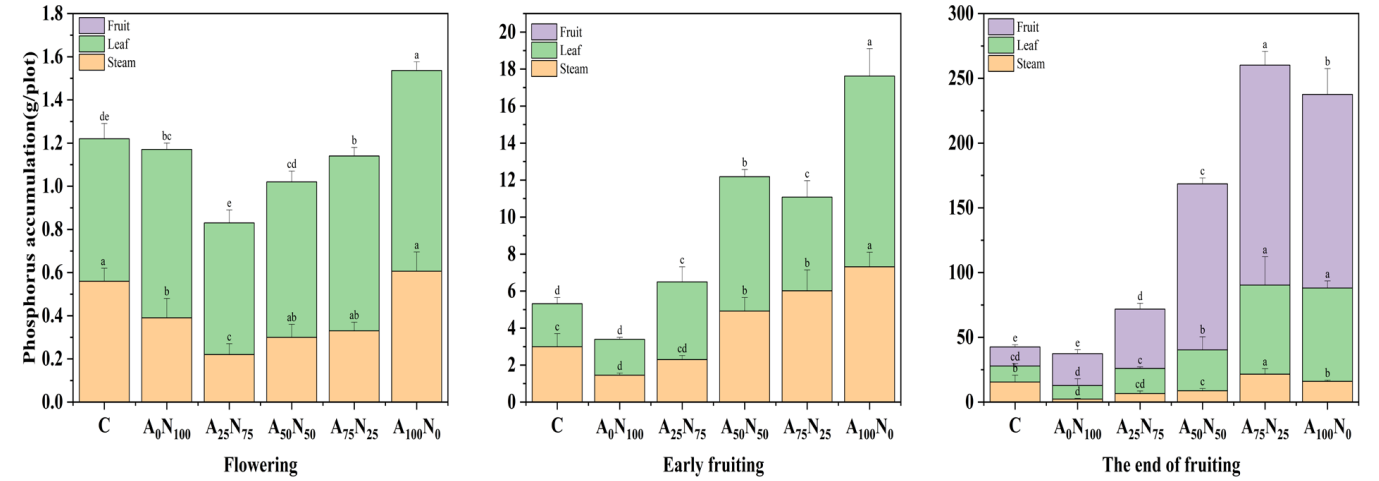


Figure 3. Phosphorus accumulation in tomatoes under different ammonium–nitrate nitrogen ratios. Note: Results are mean ± standard deviation (n = 3) and values followed by different lowercase letters (a, b, c, d, and e) within the same row are significantly different at $p < 0.05$ according to Duncan's Multiple Range Test.

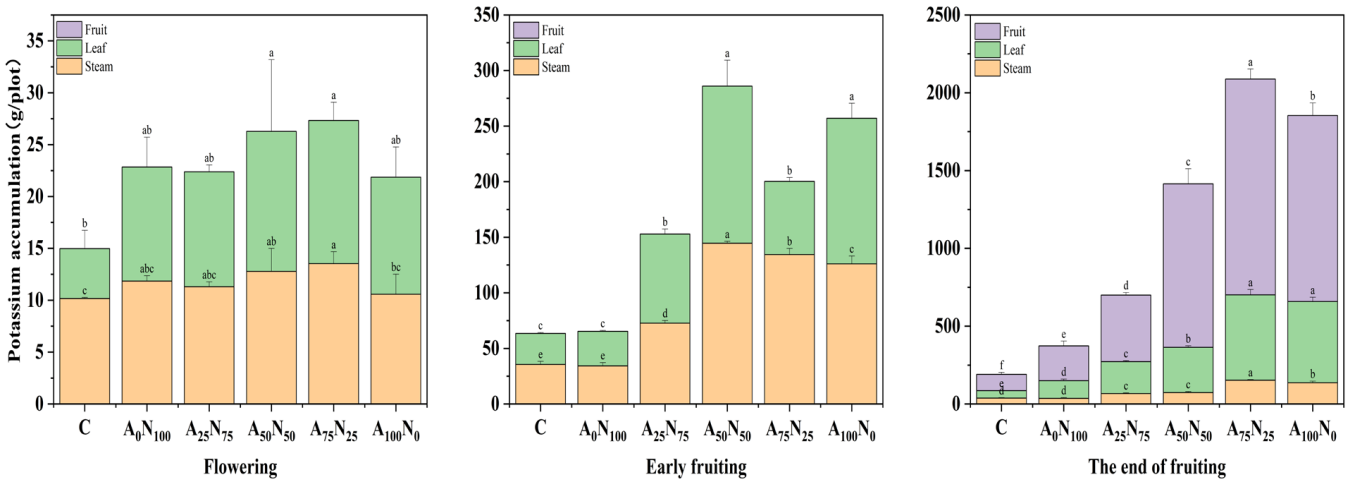


Figure 4. Potassium accumulation in tomatoes under different ammonium–nitrate nitrogen ratios. Note: Results are mean ± standard deviation (n = 3) and values followed by different lowercase letters (a, b, c, d, e, and f) within the same row are significantly different at $p < 0.05$ according to Duncan's Multiple Range Test.

3.6. Nitrogen Fertilizer Utilization Rate

The $A_{75}N_{25}$ treatment exhibited the highest nitrogen fertilizer utilization efficiency among all treatments, with significant differences observed compared with $A_{50}N_{50}$ and A_0N_{100} treatments ($p < 0.05$), while the difference from $A_{100}N_0$ was not statistically significant ($p > 0.05$), with an increase ranging from 42.1% to 82.3% (Figure 5). Still, the nitrogen fertilizer utilization rate difference was insignificant, with $A_{100}N_0$ ($p > 0.05$). The A_0N_{100} nitrogen fertilizer utilization rate was significantly lower than other treatments, indicating that the treatment with all-nitrate nitrogen fertilizer was not conducive to improving the tomato's nitrogen fertilizer utilization rate.

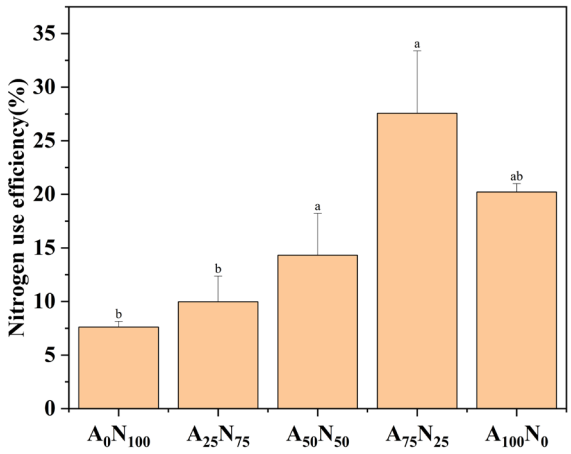


Figure 5. Nitrogen fertilizer utilization rate of tomatoes under different ammonium–nitrate ratios. Note: Lowercase letters indicate significant differences ($p < 0.05$).

4. Discussion

The findings suggest that an ammonium-to-nitrate nitrogen ratio of 75:25 may optimize tomato yield and quality in controlled greenhouse environments. However, further studies are needed on a larger scale and in different settings to confirm these results. This ratio improved nutrient accumulation and fertilizer utilization efficiency. Relevant studies have shown that A dosing is more favorable to plant growth and development than single nitrogen nutrition and promotes crop uptake and assimilation [30,31]. This study showed that $A_{75}N_{25}$ plants developed a thick and tall green morphology, which could resist toppling

and support the weight of ripe fruits, thus obtaining the highest yield; C grew short due to the lack of additional nitrogen supply; $A_{100}N_0$ tomato plants' height and stem thickness turned out to be similar to those of C, and their yield was lower, which could be attributed to the high concentration of nitrate nitrogen leading to the stunting of tomato growth. It was previously reported [32] that tomato plant growth was stunted under complete nitrate or ammonium nitrogen treatment, and the plants were prone to collapse and unable to bear the weight of fruit at a later stage. However, it was considered that the best plant shape and highest yield were obtained when the nitrogen mass ratio of ammonium nitrogen to nitrate nitrogen was 25:75, which was different from the results of the present study. This might be related to the preferences of other varieties of tomatoes for the uptake of different nitrogen forms.

Plant dry matter is the result of the accumulation and partitioning of photosynthetic products in different organs of the plant, and various nitrogen fertilizer forms and concentration treatments significantly affected the accumulation and partitioning of dry matter in tomatoes [33]. It was shown that dry matter accumulation in plants supplied with nitrate nitrogen during the first stages of fertility and ammonium nitrogen during the later period was significantly greater than in plants continuously supplied with nitrate nitrogen [34]. The present study showed that tomato plants treated with different A ratios accumulated large amounts of dry matter in stems and leaves with $A_{75}N_{25}$ from growth to the flowering stage and, at the same time, maintained relatively high dry matter accumulation in stems and leaves at the late fruiting stage, which laid a strong reservoir capacity for tomato fruit accumulation, resulting in the high yield of $A_{75}N_{25}$ tomatoes.

In this study, titratable acid in the tomatoes increased with increasing rates of ammonium fertilizer, and the highest organic acid content was found under $A_{75}N_{25}$ treatment, which may be attributed to the higher NH_4^+ inhibiting plant uptake of cations and thus increasing H^+ uptake, which increased fruit acid content [35]. Soluble sugar content increased and then decreased with the increasing ammonium fertilizer rate, with the highest soluble sugar content in tomatoes under $A_{75}N_{25}$, which may be related to the fact that ammonium-dominated nitrogen fertilizer supply can increase fruit glutamate content and further promote fruit sugar accumulation [36]. However, soluble solids decreased with the increasing percentage of ammonium nitrogen application, which may be due to antagonism of the uptake of NH_4^+ and K^+ by plants, with higher concentrations of NH_4^+ supply decreasing the uptake of K^+, which is necessary for the synthesis of soluble solids [37].

Our results are consistent with the widely accepted notion that nitrogen forms substantially impact the growth and yield of tomatoes. Recent research, including [38,39], has demonstrated that the efficacy of nutrient uptake and plant growth can be enhanced through using mixed nitrogen sources. In particular, research [40] demonstrated that the physiological functions of tomatoes are enhanced, resulting in an increase in yield and quality, when the ammonium-to-nitrate ratio is balanced. Furthermore, researchers [41] have underscored the significance of optimizing nitrogen forms to reduce environmental impacts and improve the sustainability of crops. Supported by comparison of our findings with the aforementioned studies, it is noted that the $A_{75}N_{25}$ treatment effectively enhanced tomatoes' yield while preserving a harmonious level of nutrient absorption. This equilibrium plays a pivotal role in sustaining the long-term health and productivity of the soil. Our research adds to the expanding collection of scholarly works presenting tangible proof of the advantages associated with particular ratios of ammonium to nitrate in regulated settings.

Under the same nitrogen application concentration, potassium accumulation in tomatoes was higher than nitrogen and phosphorus accumulation (Figures 2–4), indicating that tomato is a potassium-loving crop. In the late fruiting stage, $A_{75}N_{25}$ had the highest potassium accumulation in stems and fruits. An adequate potassium supply is beneficial for tomatoes to resist the support demands of higher yield and improve quality [42]. Plant uptake of both nitrogen and phosphorus increased with the increase in the ratio of ammonium fertilizer, and $A_{75}N_{25}$ fruits had the highest nitrogen and phosphorus accumulation,

indicating that application on a nitrogen mass ratio of ammonium nitrogen to nitrate nitrogen of 75:25 is conducive to the accumulation of nitrogen, phosphorus nutrients, and improving the utilization rate of nitrogen and phosphorus in tomatoes, thus reducing the environmental hazards caused by the loss of nitrogen and phosphorus during the cultivation of tomatoes in facilities [43,44].

5. Conclusions

Nitrogen fertilization significantly increased the yield of dry matter mass, the accumulation of nitrogen, phosphorus, and potassium, the soluble solids, soluble sugars, and vitamin C (Vc) content of tomatoes. Among all the treatments, $A_{75}N_{25}$ resulted in the highest tomato plant height, stem thickness, dry matter accumulation, fruit nitrogen, phosphorus and potassium accumulation, soluble sugar, and soluble solids content. The differences in yield and nitrogen fertilizer utilization rate of tomatoes under $A_{75}N_{25}$ and $A_{100}N_0$ treatment were non-significant but their values were significantly higher than the other treatments. Conclusively, our study indicates that while the $A_{75}N_{25}$ treatment optimized tomato yield and quality, high concentrations of ammonium nitrogen ($A_{100}N_0$) did not result in significant yield differences compared with $A_{75}N_{25}$. This suggests that high ammonium concentrations alone are not necessarily detrimental but may not provide additional benefits compared with a balanced nitrogen ratio.

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