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Optimizing Nitrogen for Sustainable Yield and Efficiency: Insights from Shouguang Facility-Grown Tomatoes

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Abstract: Facility-based agriculture has rapidly advanced due to its capacity for high-intensity and year-round crop cultivation. This study evaluated the effects of different nitrogen fertilizer application rates on the growth of greenhouse tomatoes, while utilizing ^{15}N tracing technology to explore nitrogen utilization efficiency during the growth process of facility-grown tomatoes. The results indicate that nitrogen application rates within the range of N60–N80 (93–128 kg N ha^{-1}) can optimally balance yield, nitrogen-use efficiency, and crop growth. Application rates exceeding this range do not enhance yield and lead to reduced nitrogen-use efficiency. Tomato plants exhibited a low N requirement during the seedling stage, relying primarily on native soil N stocks during the flowering stage. Fertilizer-derived N use increased during the fruiting stage. These findings demonstrate that excessive N inputs lead to diminishing returns and potential nutrient imbalances, while fully utilizing soil N stocks during the seedling and flowering stages is essential. This study emphasizes the importance of adjusting nitrogen input according to the developmental stages of the crop to optimize yield and resource utilization.

Keywords: nitrogen-use efficiency; facility-based tomatoes; ^{15}N-labeled fertilizer; sustainable agriculture

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1. Introduction

From the 20th century onwards, agriculture that is infrastructure-dependent, predominantly employing solar greenhouses and plastic tunnels, has undergone rapid global expansion, significantly impacting rural development and agricultural productivity [1,2]. This modern agricultural production method is characterized by high intensification, with substantial inputs, outputs, and yields, enabling continuous off-season and year-round production for fruits and vegetables [3]. Globally, greenhouse vegetable production has increased more than fivefold in recent decades [1]. This development has presented a viable solution to food scarcity in areas with limited fertility or aridity [4,5]. Therefore, adopting a balanced strategy for growers to achieve sustainable production both economically and environmentally is of great importance.

The tomato (*Solanum lycopersicum* L.), a vegetable of global significance, is widely recognized both for its widespread consumption and its prominence as a primary vegetable in greenhouse production systems [6,7]. Tomato cultivation is particularly N-intensive, with N being one of the most critical nutrients required for both maximizing yields and improving quality [8]. Studies have demonstrated that the quantity of nitrogen applied significantly affects tomato yield and quality, which includes total soluble solids, total sugar, and vitamin C content [9]. Additionally, the form of nitrogen impacts tomato growth and metabolism [10], disease resistance [11], and stress adaptation capacity [12]. Proper N management can synchronize crop N demand with N supply, enhance yields and minimize N losses [13]. Given the high economic returns of facility-based agriculture [14], local growers tend to favor yield-enhancing inputs and are often insensitive to fertilizer costs, leading to the widespread practice of excessive N fertilization [15,16]. The annual average N fertilizer input for facility-grown tomatoes varies between 1900 and 3600 kg N ha^{-1} [17], three to five times the amount typically required for vegetable crops [15]. However, the efficiency of N utilization significantly decreases with increasing fertilizer application rates [18], approximately 50% of applied N fertilizer escapes into the environment [19]. Additionally, excessive fertilization in facility-based agriculture is often coupled with flood irrigation, where each irrigation event applies approximately 60–100 mm of water [20]. Over-fertilization combined with flood irrigation leads to significant N leaching, which reduces N-use efficiency and incurs substantial environmental costs, such as eutrophication and emissions of greenhouse gases [21,22]. Researchers have demonstrated that excess N fertilizer can be converted into potent greenhouse gases like nitrous oxide (N_2O) or atmospheric pollutants like nitric oxide (NO), which significantly contribute to environmental stress [23,24]. Statistics indicate that N_2O emissions from plastic greenhouse fields contribute roughly 25% of the total agricultural N_2O emissions in China [24]. Excessive N fertilizer application can result in environmental contamination and resource inefficiency, while insufficient application may compromise crop yields. Therefore, optimizing nitrogen fertilizer application for a sustainable yield in facility-based tomato growing, while improving nitrogen-use efficiency and minimizing environmental impact, is crucial for the sustainable development of facility-based vegetable production systems.

In China, the area dedicated to greenhouse vegetable production systems has grown from 5000 hectares in 1978 to 4 million hectares in 2021, a more than 700-fold increase [8,25]. Specifically in Shandong Province, Shouguang City, recognized as the origin of solar greenhouse vegetable production in China, has significantly advanced the northern vegetable industry [26] and has established over 300,000 solar greenhouses, producing vegetables that are sold in more than 200 large and medium-sized cities across China and exported internationally. This has made Shouguang the largest base and a key national center for facility-based vegetable production in China [27]. Current research on facility-based agriculture predominantly focuses on the environmental impacts of high-input production systems, such as greenhouse gas emissions and water pollution [23,24,28,29]. Some studies also quantify the effects of N inputs on crop yields and quality [8], and the importance of soil properties in shaping the internal potential N cycle [30]. However, there is a significant research gap in quantifying N-use efficiency at various growth stages of facility-grown vegetables. Thus, understanding this variability is crucial for optimizing fertilizer use throughout the plant growth cycle.

This study investigated N-use efficiency in facility-grown tomatoes across nine critical growth stages utilizing ^{15}N tracing technology, while also quantifying the impact of different N application rates on the growth and quality of the tomatoes. The objective was to provide precise measurements of N utilization across various growth stages and offer insights into plant and fruit N uptake characteristics, ultimately establishing a precise bal-

anced fertilization strategy that optimizes N use and ensures optimal yields in controlled environments. This research aims to enhance the understanding of nitrogen dynamics and inform sustainable tomato cultivation practices, aligning with the goals of high productivity and environmental sustainability.

2. Materials and Methods

2.1. Overview of the Study Area

The experiment was conducted in a greenhouse at the Shouguang Facility Agriculture Research and Development Center of the Chinese Academy of Sciences, located in Zhaili Village, Shouguang City, Shandong Province, China (36°54′ N, 118°51′ E), which is one of the major facility-based vegetable production areas in China. This region is one of the key facility-based vegetable production areas in China. The area experiences an average annual rainfall of 610 mm, with temperatures ranging from a maximum of 38.4 °C to a minimum of −9.7 °C, and an average annual temperature of 14.1 °C. The area receives approximately 2415 h of sunlight annually, and the soil type is brown soil. The tested tomato variety was "Pantailang", which is a widely cultivated large-fruited variety in Shouguang City. Its ripening time is approximately 130–150 days.

The baseline soil for the 0–20 cm layer is shown in Table 1.

Table 1. Basic soil properties in the 0–20 cm layer.

Organic Matter	Total Nitrogen	Total Phosphorus	Total Potassium	Bulk Density	pH
22.93 g kg^{-1}	1.35 g kg^{-1}	1.51 g kg^{-1}	2.78 g kg^{-1}	1.17 g cm^3	7.19

The environmental conditions of the greenhouse during the experiment are provided in Table 2.

Table 2. Basic environmental conditions of the selected greenhouses during the test period.

	Seedling Stage	Flowering Stage (From Flowering to First Fruit Harvest)	Fruit Stage (Entire Harvest Period)
Daytime air temperature	25–30 °C	21–25 °C	23–26 °C
Nighttime air temperature	12–16 °C	14–17 °C	14–17 °C
Minimum night temperature	5 °C	8 °C	10 °C
Air humidity	80–85%	70–80%	70–80%
Soil moisture (Reference)	75–90% of soil maximum water holding capacity	80–95% of soil maximum water holding capacity	75–85% of soil maximum water holding capacity

2.2. Experimental Design

The experiment utilized precision fertilization through root-zone drip irrigation, employing an integrated system that combines drip pipes and drip arrows for both irrigation and fertilization. This method is commonly used in Chinese greenhouse cultivation due to its high degree of universality. The application of fertilizer was contingent upon the specific conditions of the production environment. In most cases, fertilizer was introduced via irrigation on a daily basis, with the exception of days characterized by cloud cover or precipitation. The tomatoes are grown in natural light and no additional artificial light is provided. The fertilization strategies were meticulously designed to align with the N

absorption patterns of the plants, thereby improving the efficiency with which fertilizer was utilized. The crop was planted in the autumn with rows spaced 140 cm apart, consisting of two rows per ridge and a plant spacing of 45 cm. Each experimental plot spanned 16.38 m^2, with 54 plants per plot, corresponding to a planting density of 33,000 plants per hectare. The fertilization levels were primarily based on the optimized substrate cultivation scheme for greenhouse tomatoes proposed by Huang et al. (2017) [31]. Based on a thorough evaluation of the results from an initial substrate trial, the standard rate of N fertilization throughout the growth cycle for greenhouse-grown tomatoes was determined to be 147.85 kg N ha^{-1}. The daily standard fertilization rate per plant throughout the entire growth period is detailed in Table 3.

Table 3. Standard water, P and K fertilizer application rates for plot experiments (per plant per day).

Growth Stage	Seedling Stage	Flowering Stage (From Flowering to First Fruit Harvest)	Fruit Stage (Entire Harvest Period)
Duration	30 days	88 days	54 days
Pure P usage (g/day/plant)	0.0142	0.0223	0.0230
Pure K usage (g/day/plant)	0.0228	0.1405	0.2103
Water usage (L/day/plant)	0.1627	0.5858	0.7510

The experiment was divided into two segments: a ^{15}N labeling experiment and a plot cultivation experiment. The ^{15}N labeling experiment was based on the conventional N application rate, and each treatment was replicated three times. The ^{15}N labeling experiment used a labeled urea with 5.14 atom% ^{15}N (Shanghai Chemical Research Institute Co., Ltd. Shanghai, China), and each replicate covered an area of 32.76 m^2. In the plot cultivation experiment, each treatment replicate, covering an area of 16.38 m^2, was designed with different percentages of N rates relative to conventional baseline rates, i.e., N40, N60, N80, N100, N120 (Figure 1). All plot cultivation and ^{15}N labeling experiments received equal amounts of organic fertilizers and phosphorus-potassium fertilizers, of 285 kg N ha^{-1} from organic fertilizer, 170 kg P_2O_5 ha^{-1}, and 735.79 kg K_2O ha^{-1}, respectively. Pest control and production management were kept consistent across all treatments.

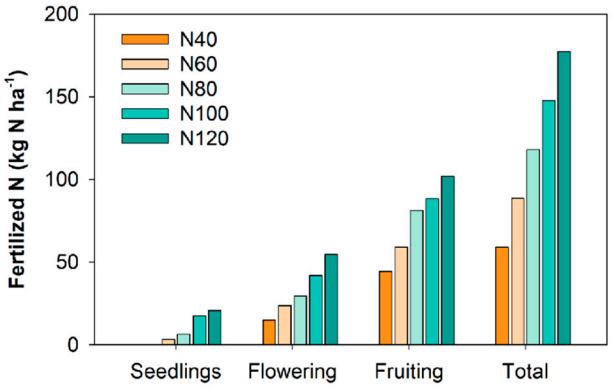

Figure 1. The amount of fertilizer N application under different N treatments during different growth stages.

2.3. Sample Collection and Determination

In the plot cultivation experiment, samples were collected three times during the tomato growing season: at the seedling, flowering, and fruiting stages. For each sampling

event, three tomato plants were selected, and at the fruiting stage, all remaining plants (i.e., 48 plants) were harvested for yield measurement. In the ^{15}N labeling experiment, a total of nine samples were collected, i.e., three samples from each growth stage of seedling, flowering and fruiting. Two plants were collected at each sampling event. Ten plants were harvested in the final sampling for yield measurement. The specific sampling dates are detailed in Table 4.

Table 4. Specific sampling date during different growth stages.

Growth Stage	Plot Cultivation Experiment	^{15}N Labeling Experiment
Seedling stage	12 December 2019	23 November 2019 2 December 2019 12 December 2019
Flowering stage (from flowering to first fruit harvest)	9 March 2020	31 December 2019 11 February 2020 7 March 2020
Fruit stage (entire harvest period)	7 May 2020	19 March 2020 13 April 2020 7 May 2020

All sampling was performed destructively. Specifically, plants were dug up with their roots intact, thoroughly cleaned, and then dried. After drying, the aboveground and underground parts were separated. Each part was then individually ground and sieved to a particle size of <0.150 mm for storage. Total N content was determined using an Elemental Analyzer (VarioMACRO cube, Elementar Analysensysteme GmbH, Langenselbold, Germany), while ^{15}N abundance was measured using a Finnigan Delta plus XP stable isotope ratio mass spectrometer (Thermo Finnigan, San Jose, CA, USA). To avoid cross-contamination, samples were analyzed in ascending order of abundance.

The 2,6-dichlorophenolindophenol (DCPIP) method was employed to determine vitamin C content in tomato fruits, whereas UV–Vis spectrophotometry was utilized to determine the concentrations of nitrate and nitrite.

2.4. Data Analysis and Calculations

The N uptake by different parts of the plants under each treatment in the plot experiments was calculated using the following formula:

$$N_{uptake} = M \times N_{total}/1000$$

where N_{uptake} is the total N uptake (plant or fruit) (kg N ha^{-1}), M is the dry matter weight of the plant or fruit (kg ha^{-1}), N_{total} is the N concentration in the plant or fruit (g kg^{-1}).

Relative N fertilizer uptake rate was calculated using the following formula:

$$R = (X - CT)/Y \times 100\%$$

where R is the relative N fertilizer uptake rate (%), X is the total N uptake (plant N + fruit N) of fertilization treatment (kg ha^{-1}) in fruiting stage, CT is the total N uptake of CT treatment in fruiting stage (kg ha^{-1}), Y is the N input of chemical fertilizer each treatment.

In the ^{15}N labeling experiment, the amount of N fertilizer absorbed by the plants and the N fertilizer-use efficiency were calculated using the following formulas:

$$N_{plant} = \sum N_x \times \frac{b - c}{a - c} \quad (1)$$

$$\text{NUE}\ (\%) = \frac{N_{plant}}{N_{fertilizer}} \times 100 \quad (2)$$

where N_{plant} is the amount of N fertilizer absorbed (kg ha^{-1}), Nx is the total N uptake by the different parts of plant (kg N ha^{-1}), b is the ^{15}N abundance in different parts of the plant (atom%), a is the ^{15}N abundance of the applied labeled urea (atom%), c is the natural abundance of ^{15}N (atom%), $N_{fertilizer}$ is the amount of applied N fertilizer (kg N ha^{-1}).

Before conducting the analysis, the Kolmogorov–Smirnov test was assessed to ensure the normality of the data, while Levene's test was used to check the homogeneity of variances. LSD's multiple comparison post hoc test was employed to detect significant differences between the treatment means ($p < 0.05$). All statistical analyses were carried out using R version 4.2.1.

3. Results

3.1. Dry Weight of Plants and Fruits

The plant and fruit dry weights of the tomatoes showed significant differences between the various N treatments at different growth stages (Figure 2). Specifically, the plant dry weight at the seedling stage ranged from approximately 210 to 270 kg ha^{-1}. The dry weights of N100 and N120 treatments were significantly lower than those under N60 ($p < 0.05$). At the flowering stage, plant dry weight increased to 2800–3300 kg ha^{-1}, showing substantial growth compared to the seedling stage. The dry weights at the flowering stage under N60, N100, and N120 treatments were significantly higher than those under CT and N80 treatments ($p < 0.05$). At the fruiting stage, the plant dry weight reached 4600–6900 kg ha^{-1}, with the CT group being significantly lower than all N-treated groups ($p < 0.05$). Plant dry weights at the fruiting stage under N80 and N120 treatments were significantly higher than those under the lower N application rate of N40 ($p < 0.05$). The dry weight of the fruits ranged from 4900 to 5800 kg ha^{-1}, with no significant differences between the N treatments ($p > 0.05$).

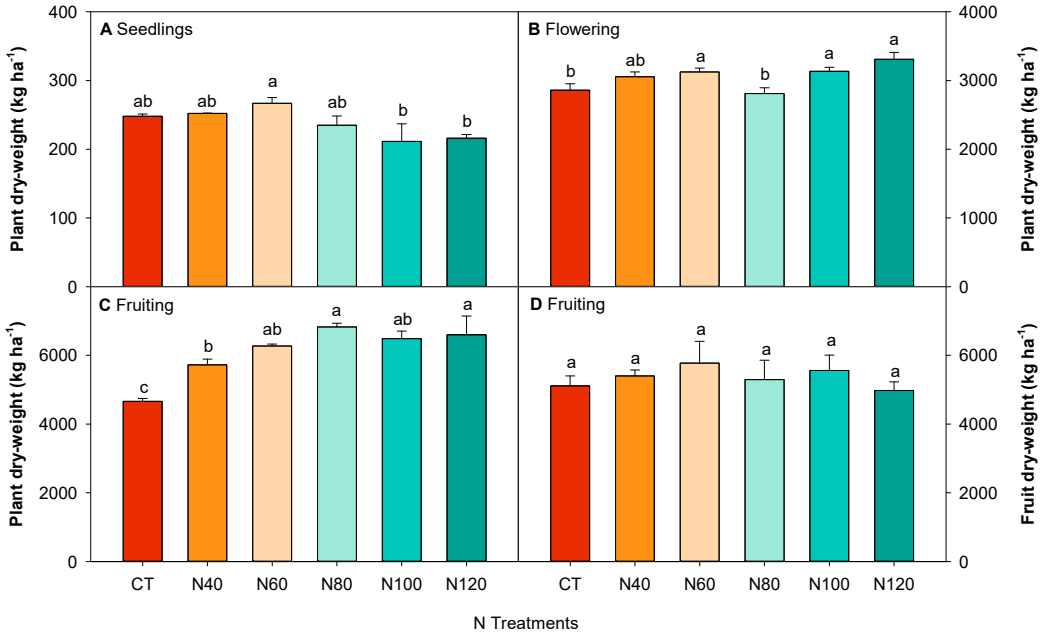

Figure 2. Plant (**A**–**C**) and fruit (**D**) dry weights under different N treatments at seedling, flowering, and fruit stages. Different letters indicate significant differences at $\alpha = 0.05$. Error bars indicate standard errors (n = 3).

3.2. N Content and Yield of Plants and Fruits

The N contents in plants and their fruits also showed significant differences between the N treatments at different growth stages (Figure 3). At the seedling stage, the plant N content under the N60 treatment was the highest, significantly exceeding those under N80, N100, and N120 treatments ($p < 0.05$). Overall, the N contents were ranked as follows: N60 (13.9 kg N ha^{-1}) > N40 (13.0 kg N ha^{-1}) > CT (12.8 kg N ha^{-1}) > N80 (11.3 kg N ha^{-1}) > N100 (10.9 kg N ha^{-1}) > N120 (10.8 kg N ha^{-1}). Plant N contents at the flowering stage ranged from 90.3 to 127.1 kg N ha^{-1}, representing an increase of 6–10-fold compared to the seedling stage. The rate of increase was highest under N120 (1033%), followed by N100 (1018%), N80 (799%), N40 (694%), N60 (684%), and CT (652%). The N content under the N120 treatment (121.9 kg N ha^{-1}) was significantly higher than those under CT (96.2 kg N ha^{-1}), N40 (103.3 kg N ha^{-1}), N60 (108.9 kg N ha^{-1}), and N80 (101.2 kg N ha^{-1}) during this period ($p < 0.05$).

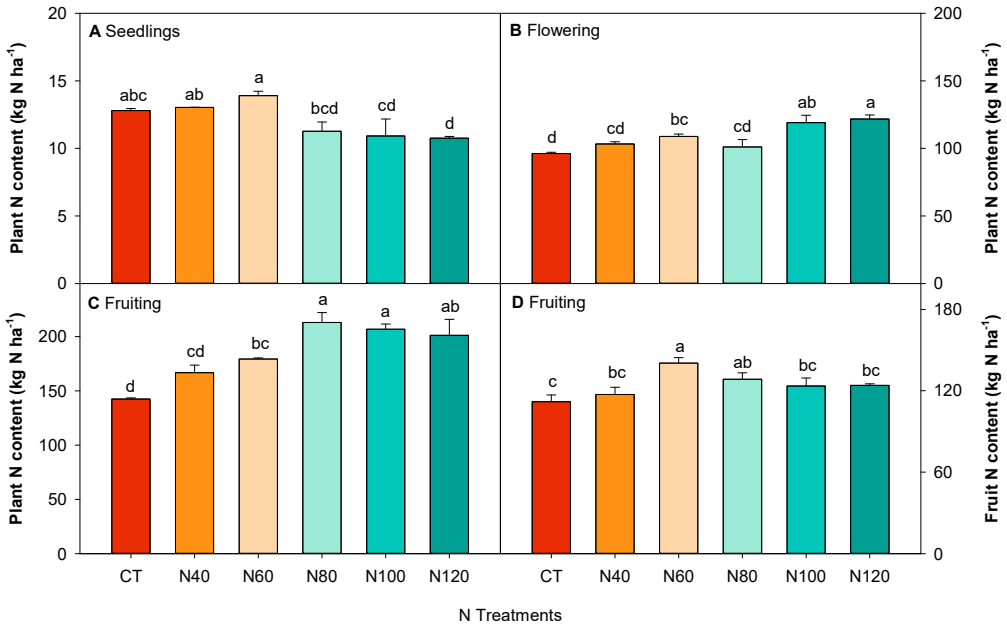

Figure 3. Plant (**A**–**C**) and fruit (**D**) N contents under different N treatments at seedling, flowering, and fruit stages. Different letters indicate significant differences at $\alpha = 0.05$. Error bars indicate standard errors (n = 3).

Generally, N contents in plants at the fruiting stage (140.3–229.6 kg N ha^{-1}) increased compared to the seedling (10–15 kg N ha^{-1}) and flowering stages (100–150 kg N ha^{-1}). The N80 treatment exhibited the highest increase of 110%, whereas other N addition treatments showed increases of approximately 60–70%, with the CT treatment having the lowest increase at 48%. The N contents were significantly higher in plants under moderate and high N applications, such as N80 (212.9 kg N ha^{-1}), N100 (206.8 kg N ha^{-1}), and N120 (201.1 kg N ha^{-1}) than CT (142.5 kg N ha^{-1}), low N treatments of N40 (166.7 kg N ha^{-1}) and N60 (179.4 kg N ha^{-1}) ($p < 0.05$). The N content of the fruit was highest under the N60 treatment (140.3 kg N ha^{-1}), significantly exceeding those of CT (111.9 kg N ha^{-1}), N40 (117.2 kg N ha^{-1}), N100 (123.5 kg N ha^{-1}), and N120 (123.9 kg N ha^{-1}) ($p < 0.05$). Additionally, the proportion of the fruits' N content relative to the total crops' N content was highest in the CT and N60 treatments, both reaching 44%. In contrast, the proportions in the N80, N100, and N120 treatments were 37.7%, 37.4%, and 38.3%, respectively.

Generally, tomato yields were approximately 91–110 t ha^{-1}, with no significant difference observed between the N treatments (Figure 4A, $p > 0.05$). The N fertilizer uptake as a percentage of total input was also calculated using the CT with no N fertilizer input

as a control (Figure 4B). The highest N fertilizer uptake was observed at moderate N application rates (N60 and N80). The N uptakes were even less at higher N fertilizer inputs of N100 and N120.

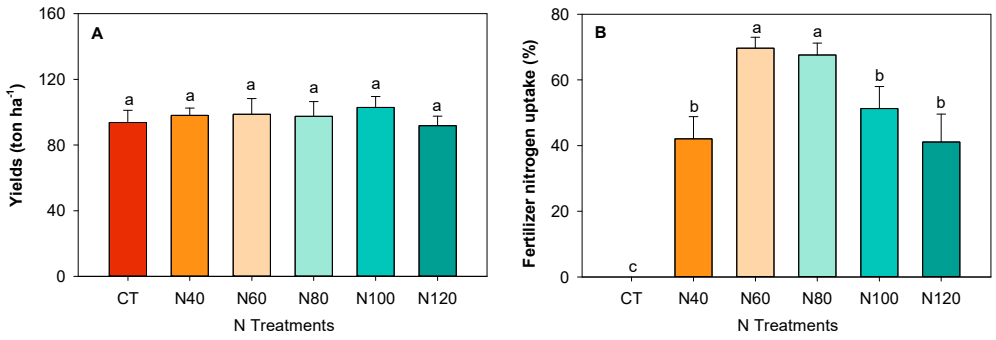

Figure 4. Tomato yields (**A**) and relative N fertilizer uptake rates (**B**) under different N treatments. Different letters indicate significant differences at $\alpha = 0.05$. Error bars indicate standard errors (n = 3).

3.3. Fruit Quality

No significant differences in vitamin C content were observed in tomato fruits across the different treatments (Figure 5, $p < 0.05$). Decreasing nitrogen application did not result in a significant reduction in vitamin C content in the fruits.

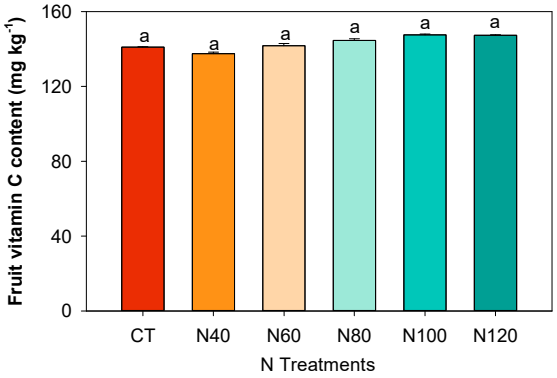

Figure 5. Vitamin C content of tomato fruit under different N treatments at seedling, flowering, and fruit stages. Letters indicate significant differences at $\alpha = 0.05$. Error bars indicate standard errors (n = 3).

The nitrite and nitrate contents of the tomato fruit in the CT treatment were significantly lower compared to those in other treatments (Figure 6, $p < 0.05$). Specifically, the nitrite content varied between 1.5 and 3.5 mg kg^{-1}, whereas the nitrate content was in the range of 25 to 35 mg kg^{-1}, which is far below the WHO standard limit of 500 mg kg^{-1}.

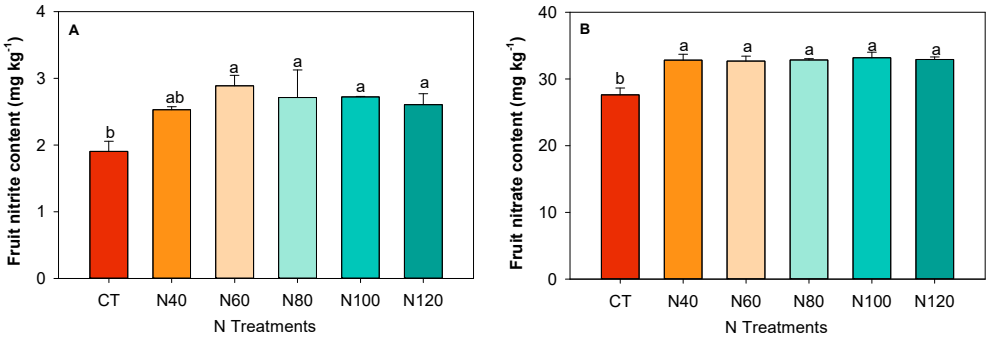

Figure 6. Nitrite (**A**) and nitrate (**B**) content of tomato fruit under different N treatments at seedling, flowering, and fruit stages. Different letters indicate significant differences at $\alpha = 0.05$. Error bars indicate standard errors (n = 3).

3.4. Dynamic of Total N and Urea-Derived N

To better understand the dynamic changes in N contents and the absorption of fertilizer-derived N at different growth stages, the variations in plant total N content and urea-derived N were calculated throughout the growing season (Figure 7). The plant total N content was nearly negligible during the seedling stage, with no significant increase observed within this period. As previously described, the flowering stage marked the most substantial accumulation of plant N content, reaching its peak at 115–130 days with a maximum of 153.4 kg N ha^{-1}. Meanwhile, the fruit N contents showed a steady increase from 92 to 178 days, with significant increments observed between each measurement ($p < 0.05$), reaching its maximum value of 116.5 kg N ha^{-1} at 178 days.

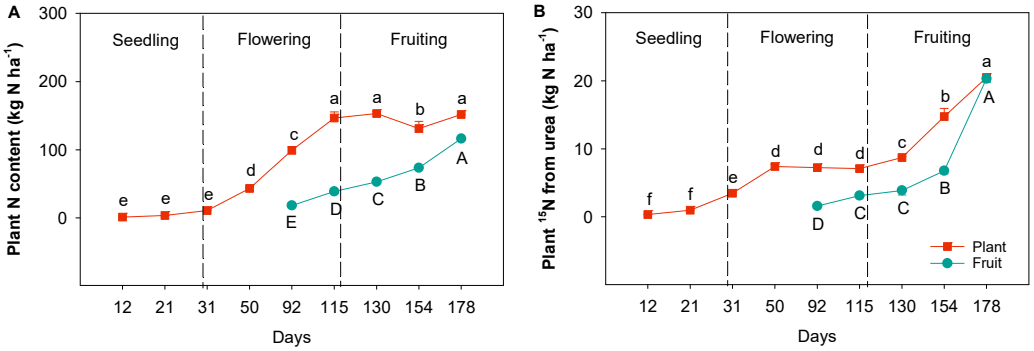

Figure 7. Plant and fruit total N contents (**A**) and ^{15}N contents from urea (**B**) on different sampling days. Different letters indicate significant differences at $\alpha = 0.05$ between different sampling days. Error bars indicate standard errors (n = 3).

Plant ^{15}N from urea showed significant increases from 21 days (0.9 kg N ha^{-1}) to 50 days (7.4 kg N ha^{-1}) and from 115 days (7.2 kg N ha^{-1}) to 178 days (20.2 kg N ha^{-1}) ($p < 0.05$). Overall, the absorption and utilization of urea during the fruiting stage were higher than those during the seedling and flowering stages. The trend of fruit ^{15}N from urea closely matched that of fruit N content, with significant differences observed between each sampling point from 92 to 178 days ($p < 0.05$). However, from 154 to 178 days, the increase in fruit ^{15}N from urea (13.8 kg N ha^{-1}) was substantially greater than during other periods by 2–6-fold.

3.5. Dynamic of N-Use Efficiency in Plants and Fruits

The staged N-use efficiency (NUE) and the cumulative NUE were significantly different on each sampling day throughout the entire growth cycle (Figure 8). The staged plant NUE gradually increased during the seedling stage, reaching its peak at approximately 40% in 31 days (Figure 8A). However, it significantly decreased during the flowering stage, hitting its lowest points around 92 and 115 days. During the fruiting stage, the staged NUE recovered slightly to about 12.2–17.2% at 130–178 days. Meanwhile, the staged NUE of the fruit decreased significantly to around 4.7% between 115 and 130 days ($p < 0.05$) but then sharply increased from 154 to 178 days, reaching a maximum of 40%.

The cumulative NUE of plants followed a unimodal pattern (Figure 8B). It shows a significant increase ($p < 0.05$) from 12 days at 5.2% to 50 days at 21.8%, followed by a significant decrease ($p < 0.05$) from 50 days to 115 days at 12.1%, and a slight increase from 115 days to 178 days at 13.8%. The peak cumulative NUE was observed at 50 days, around 22%. For the fruit, cumulative NUE significantly increased from 92 days at 3.7% to 115 days at 5.1%, and from 154 days to 178 days at 13.8% ($p < 0.05$), with no significant changes observed between 115 and 154 days.

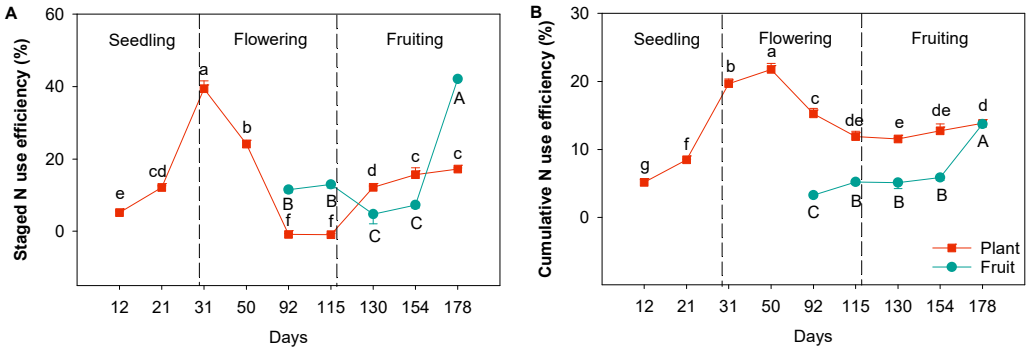

Figure 8. Staged (**A**) and cumulative N-use efficiency (**B**) of plant and fruit on different sampling days. Different letters indicate significant differences at $\alpha = 0.05$ on different sampling days. Error bars indicate standard errors (n = 3).

4. Discussion

4.1. Responses of Tomato Yield and Quality to Nitrogen Application

Previous research has demonstrated that increased N application positively influences tomato yields and fruit characteristics [32]. However, some studies have shown an opposite trend, suggesting that nitrogen-use efficiency (NUE) and crop yield can be enhanced at moderate rather than maximum N application rates [33]. The supply of N exceeding the optimal application rate did not significantly increase tomato yield [8]. These different results can be attributed to variations in initial soil nitrogen status and other regional characteristics, which may lead to disparate responses in the plant nitrogen content to nitrogen fertilization.

In the fruiting stage, the demand for N increases significantly to support both vegetative growth and fruit development. Studies have shown that most of the N absorbed during fruit development comes from recently applied N fertilizer rather than stored N in the plant [34]. As a result, the fruit nitrogen content showed a significant increase with higher chemical nitrogen application rates [35]. This highlights the crucial role of sufficient nitrogen supply during the fruiting stage to support ongoing crop growth.

It is noteworthy that there were no significant differences in fruit dry weight and yield across the N treatments, as shown in Figures 2 and 4. Studies have confirmed that the nitrogen content in the leaves increases as the level of nitrogen application rises [35]. Under high N conditions, plants may allocate excess N resources to vegetative growth, i.e., stem and leaf development, reducing the proportion of N available for fruit development. Meanwhile, excessive N can prolong the vegetative growth phase, consuming substantial nutrients, and inhibiting flower bud differentiation, thereby reducing fruit set and yield [36]. This may partially explain why, despite sufficient N supply, fruit yield did not significantly increase.

The study results indicate that the application of excessive N fertilizer did not lead to an increase in either fruit dry weight or yield (Figures 2D and 4A). Regarding nitrate and nitrite content, increasing the N application did not pose a higher safety risk to the fruit (Figure 6). However, the utilization efficiency of the nitrogen fertilizer was significantly lower in the N100 and N120 treatments compared to moderate nitrogen application rates (Figure 4B). These results align with previous findings that excessive N does not enhance productivity but rather reduces NUE and leads to a resource waste [18,23]. In addition to diminishing returns on yield and nitrogen-use efficiency, excessive nitrogen application poses significant environmental risks. Studies have shown that surplus nitrogen not utilized by plants can leach into groundwater as nitrate, contributing to water contamination and eutrophication. Furthermore, excessive nitrogen inputs can result in increased emis-

sions of greenhouse gases like nitrous oxide (N_2O), which significantly contribute to global warming [21,22].

4.2. Dynamic Utilization of Nitrogen in Tomatoes

The single most significant factor contributing to excessive nitrogen loss in annual cropping systems is likely the misalignment between nitrogen availability and the crop requirements [37]. In this study, the N content and its dynamic changes in both plants and fruits during different growth stages provide valuable insights into N use patterns under different fertilization regimes.

It is worth noting that the increase in N in seedlings was minimal (Figure 7), while the nitrogen content under low-nitrogen treatment was significantly higher compared to that under high-nitrogen treatment (Figure 3). This indicates that reduced N inputs may facilitate more effective N uptake during the initial growth phases [38]. Furthermore, the results of NUE demonstrate a consistent increase during this stage, emphasizing the necessity of adapting fertilization strategies to align more closely with the plant's N needs during pivotal early developmental stages. Therefore, by reducing the amount of nitrogen fertilizer applied during the seedling stage and postponing the nitrogen application period, it is possible to optimize the use of nitrogen fertilizer and potentially increase yield in the later growth stages [39].

During the flowering stage, the N content in plants increases sharply, indicating a critical period for N demands from tomatoes. Previous research has demonstrated a U-shaped relationship between N supply and flowering time [40], a finding corroborated by this study. When examining the periodic NUE, it becomes evident that most of the N use during this stage was driven by fruit development, as N uptakes by vegetative growth ceased after the fruit formation. Due to the sustained application of nitrogen fertilizers throughout the growth stage, cumulative NUE actually declined during the flowering stage. The original nitrogen reservoir in the soil during the flowering stage provides the necessary nitrogen for plant growth. Therefore, the nitrogen applications can be correspondingly reduced during this stage. Additionally, N fertilizers need to be converted into plant-available forms like ammonium and nitrate [41]. Therefore, N applied before the flowering stage may not be fully utilized in the early flowering phase due to delayed conversion, leading to reduced cumulative NUE during this stage [42].

As shown in Figure 7, the increase in the N content during the fruiting stage is predominantly observed in the fruit rather than the plant, consistent with previous findings that N in fruit accounts for 30% of the plant's total N [43]. During the fruiting stage, both the plant and the fruit exhibited a marked increase in N derived from urea (Figure 7B). We believe that increasing nitrogen fertilizer input during the fruiting stage is a feasible management measure, and we also recommend strengthening nitrogen management in the early stages to meet the nitrogen demand during the fruiting stage, ensuring normal growth and development of the fruit [43].

This study provides valuable insights into optimizing nitrogen management in facility-grown tomatoes and contributes to improving nitrogen-use efficiency in intensive agricultural systems. However, several limitations should be acknowledged that may affect the generalizability of the findings. First, the results are based on a specific greenhouse environment, and factors such as soil type, climate conditions, and irrigation practices, which vary across different greenhouse systems, could influence nitrogen dynamics. As a result, the nitrogen application rates used in this study (e.g., CT, N40, N60) may not fully represent the nitrogen needs of all greenhouse systems, especially in regions with differing environmental conditions or cultivation practices, such as hydroponics or open-field systems. Additionally, while the study focused on a single tomato variety, genetic factors can

significantly affect nitrogen-use efficiency, and different cultivars may respond differently to nitrogen inputs. Future research should expand these findings to include a broader range of greenhouse systems, environmental conditions, and tomato cultivars to refine and validate nitrogen management strategies across diverse settings.

5. Conclusions

The ^{15}N tracer experiments indicated that tomato N demand was low at the seedling stage, then increased at the flowering stage, with the primary source of N being the soil native N. Fertilizer-derived N uptake increased during the fruiting stage, along with N transfer from the plant to the fruit. Plot experiments have demonstrated that the optimal nitrogen input range of N60–N80 balances growth, yield, and sustainability. Excessive N application does not provide additional benefits to greenhouse tomato production and may reduce N-use efficiency while increasing environmental stress. Therefore, based on the findings, the following fertilization recommendations are proposed:

- Nitrogen input control: total nitrogen application should be kept between N60 and N80 over the entire growth period.
- Precise regulation in stages:
  - Seedling stage: omits chemical nitrogen fertilizer.
  - Flowering stage: apply minimal nitrogen fertilizer to meet essential nitrogen demands.
  - Fruit stage: increase nitrogen fertilizer input to meet the elevated nitrogen demands.

These findings advocate for nitrogen management strategies that match plant developmental stages to maximize yields and minimize environmental risks. Future studies should aim to refine these strategies through long-term trials and explore the role of precision agriculture in optimizing nitrogen use in controlled environments.

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