Effects of Cultivation Years on Tomato Growth and Soil Nitrogen Supply Capacity in Newly Built Solar Greenhouses (Postprint)

Authors: Wang Shichao, Chen Zhujun, Cai Hongming, Zhou Jianbin

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Abstract

To evaluate the effects of cultivation duration on the soil nitrogen supply capacity of newly constructed solar greenhouses, a combined method of pot bioassay depletion experiments and intermittent leaching aerobic incubation was employed to investigate changes in the nitrogen supply capacity of the topsoil layer (0–20 cm) in solar greenhouses of different ages in Yangling, Shaanxi (samples were taken from the field before greenhouse construction and during the 2nd and 3rd years after construction). The results indicated that with increasing greenhouse cultivation duration, both tomato biomass and nitrogen uptake increased significantly compared with pre-cultivation conditions. Specifically, tomato plant height, stem diameter, above-ground and root biomass, and leaf SPAD values in the 2nd and 3rd years were significantly higher than those before greenhouse construction, while no significant differences were observed between the 2nd and 3rd years. Nitrogen uptake by tomatoes in the 2nd and 3rd year greenhouses was 2.53 and 3.01 times that of the pre-construction field, respectively. Compared with the soil before planting, organic matter, total nitrogen, and readily available nutrient contents in the 3rd-year greenhouse soil increased significantly; the mineralizable nitrogen content in the 2nd and 3rd year greenhouse soils was 2.84 and 2.96 times that of the pre-construction field, respectively, demonstrating that the nitrogen supply capacity of greenhouse soil was significantly enhanced with increasing cultivation duration. Correlation analysis revealed that soil organic matter, total nitrogen, initial mineral nitrogen, and cumulative mineralized nitrogen were all extremely significantly positively correlated with tomato nitrogen uptake, with the correlation coefficient between cumulative mineralized nitrogen and tomato nitrogen uptake being the largest, indicating that these indicators can all be used to evaluate soil nitrogen supply capacity. As cultivation duration increases, the nitrogen supply capacity of solar greenhouse soil improves significantly, and nitrogen fertilizer application rates should be appropriately reduced in production practice with increasing greenhouse cultivation duration.

Full Text

Abstract

Solar greenhouses, developed by Chinese farmers and scientists in the early 1980s, enable winter vegetable production without additional heating or lighting across much of northern China. The high profitability of greenhouse cultivation has driven rapid expansion, with the area under solar greenhouse production increasing dramatically over the past three decades. However, intensive vegetable production in these systems typically involves excessive application of inorganic fertilizers and manure, leading to increased soil organic matter and accumulation of nutrients and salts. This nutrient accumulation, particularly nitrate, poses significant environmental risks. Optimizing nitrogen (N) fertilizer application is therefore critical for sustainable production, as mineralized N during crop growth substantially contributes to plant N uptake. Understanding N mineralization in solar greenhouse soils with different cultivation histories is essential for rational N fertilization, yet most research has focused on arable soils, leaving knowledge gaps regarding greenhouse systems.

This study evaluated the effects of cultivation duration on N supply capacity in the 0–20 cm soil layer of newly built solar greenhouses in Yangling, Shaanxi, using both pot depletion and Stanford and Smith aerobic incubation methods. Soil samples were collected before construction (0 year) and after 2 and 3 years of operation. Tomato response to cultivation history was also investigated. Results showed that plant height, stem diameter, aboveground and root biomass, and leaf SPAD values in the 2- and 3-year greenhouses were significantly higher than pre-construction field conditions, though differences between the 2- and 3-year treatments were not significant. Total N uptake increased with greenhouse age, with 2- and 3-year treatments showing 2.53- and 3.01-fold increases, respectively, compared to pre-construction soils. Soil organic matter, total nitrogen, and available nutrient contents increased significantly after 3 years of cultivation. Mineralizable N in 2- and 3-year greenhouse soils was 2.84 and 2.96 times higher than in pre-construction soils, indicating substantially enhanced N supply capacity with cultivation duration.

Correlation analysis revealed highly significant positive relationships between tomato N uptake and soil organic matter, total N, initial mineral N, and cumulative mineralized N ($P<0.01$), with the strongest correlation observed for cumulative mineralized N. These findings indicate that all these parameters can serve as indicators of soil N supply capacity, with mineralized N being the most reliable. To reduce N losses and improve use efficiency, inorganic N fertilizer inputs should be decreased as greenhouse cultivation years increase.

Keywords: Solar greenhouse; Cultivation year; Soil nitrogen supply ability; Nitrogen uptake; Growth; Tomato

Introduction

China’ s protected cultivation has expanded rapidly, reaching approximately 4.0 million hectares in 2011—nearly 600 times the area in 1980—and continues to grow at 10% annually. The northwest region represents a major advantage area for protected vegetable production, with Shaanxi Province alone having over 53,000 hectares of solar greenhouses. However, excessive fertilization, particularly nitrogen, has become increasingly problematic, with some greenhouses receiving N inputs exceeding crop requirements by fivefold. This over-application reduces N use efficiency, decreases economic returns, and causes nitrate accumulation in soils while compromising vegetable quality. Rational N management is therefore a priority for sustainable greenhouse production.

Soil N supply capacity serves as both a critical basis for determining fertilizer rates and an important indicator of soil fertility. Under long-term excessive N fertilization and irrigation in solar greenhouses, altered soil temperature and moisture regimes inevitably affect N supply capacity with increasing cultivation years. Previous surveys in Yongqing County, Hebei, showed that soil organic matter increased continuously with cucumber cultivation duration, with total N content doubling after 13 years compared to pre-planting levels, thereby enhancing soil N supply. Clarifying soil N supply characteristics and crop uptake patterns is essential for improving yields while reducing N losses.

Most research on soil N supply has focused on arable soils, with limited studies on solar greenhouse systems. Few reports have examined the effects of cultivation years on soil N supply capacity through continuous, long-term monitoring. Many existing studies have used a “space-for-time”approach, collecting numerous soil samples from greenhouses of different ages simultaneously to evaluate cultivation effects. While this method shortens research timelines, substantial variations in fertilization practices among different greenhouses introduce significant experimental errors. Therefore, 定点连续研究 (fixed-point continuous research)—collecting samples from the same greenhouses annually from construction onward—is necessary to accurately characterize changes in soil N supply capacity over time.

Various methods exist for assessing soil N supply capacity. The biological depletion method, which involves continuous cropping to evaluate soil N characteristics, represents a fundamental approach for assessing N availability. Stanford and Smith’ s intermittent leaching aerobic incubation method is widely used for evaluating soil N supply capacity under laboratory conditions by determining N mineralization potential. This study combined both methods to evaluate changes in soil N supply capacity with increasing cultivation years in solar greenhouses in Yangling, southern Loess Plateau, providing a reliable basis for rational N management in greenhouse systems.

1.1 Soil Samples

Soil samples were collected from a protected vegetable production base in Yangling, southern Loess Plateau. The region has a continental monsoon climate at approximately 520 m elevation, with mean annual precipitation of 630 mm concentrated in July-September and mean annual temperature of 12.9°C. Soils are classified as *Lou soil*. Most solar greenhouses were built in 2009-2010. During construction, the original topsoil (0–90 cm) was removed for insulation walls, resulting in low nutrient concentrations in the 0-20 cm cultivation layer: organic matter 8.3 $g \cdot kg^{-1}$, total N 0.59 $g \cdot kg^{-1}$, nitrate-N 21.2 $mg \cdot kg^{-1}$, available P 5.0 $mg \cdot kg^{-1}$, and available K 123.6 $mg \cdot kg^{-1}$. Except for available K, all nutrients were severely deficient.

Individual greenhouses typically cover 350–700 m^2, predominantly planted with tomato (*Lycopersicon esculentum* Mill.). Transplanting occurs around October each year, with harvest in late June of the following year. Yields range from 100-180 $t \cdot hm^{-2}$, averaging 145 $t \cdot hm^{-2}$. Organic fertilizers (primarily commercial chicken and cattle manure) are applied at approximately 142 $t \cdot hm^{-2}$ annually. Chemical fertilizers include compound fertilizer, urea, and potassium sulfate, with N, P_2O_5, and K_2O application rates of 690, 720, and 759 $kg \cdot hm^{-2}$, respectively. N and K fertilizers are applied as both base and top dressings, while P fertilizer and organic manure are incorporated before soil preparation.

Thirteen representative 0–20 cm soil samples were selected: 10 greenhouses built in 2009 and 3 built in 2010. Samples were collected before planting and after harvest in years 2 and 3 (2009, 2011, and 2012), representing cultivation durations of 0, 2, and 3 years, with 1, 3, and 10 greenhouses sampled, respectively. At each greenhouse, three points were sampled and composited. Fresh samples were cleared of vegetable residues, air-dried, and passed through a 2 mm sieve for nutrient analysis.

1.2.1 Pot Depletion Experiment

Pot depletion experiments were conducted using the collected soil samples with tomato as the test crop, grown continuously for three harvests. Three treatments represented 0, 2, and 3 years of greenhouse cultivation, with five replicates each. No nitrogen fertilizer was applied; all treatments received phosphorus and potassium at 0.15 g $P_2O_5 \cdot kg^{-1}$ soil and 0.15 g $K_2O \cdot kg^{-1}$ soil as calcium superphosphate and potassium sulfate, respectively.

Experiments were conducted in a net room at the College of Natural Resources and Environment, Northwest A&F University. Plastic pots (15 cm inner diameter, 20 cm height, with bottom) were filled with 1.5 kg soil mixed thoroughly with fertilizers. Deionized water was added to maintain soil moisture at 80% of field capacity. The first tomato crop ('Jin Peng 11') was sown on September 24, 2012, with 10 seeds per pot, thinned to 5 plants after emergence. Moisture was controlled gravimetrically using deionized water. The first harvest occurred on November 22, when plants were separated into shoots and roots, weighed fresh, then dried for biomass and total N determination.

After the first harvest, shoots were removed, and soil from each pot was sieved (2 mm) to remove roots, then returned to the original pots without fertilizer addition. The second crop was grown from March 16 to June 10, 2013, and the third from August 30 to November 15, 2013, using identical procedures. Total cultivation time was 222 days.

Plant height, stem diameter, and chlorophyll content (SPAD) were measured periodically, beginning 20 days after transplanting and continuing at 15-day intervals. One representative plant (weak, medium, and strong growth) was selected from each pot at each sampling, with values averaged. Soil samples were collected after each harvest for determination of available N and total N.

1.2.2 Long-term Aerobic Incubation

The Stanford and Smith intermittent leaching aerobic incubation method was employed. Fifteen grams of air-dried soil (1 mm) were mixed with an equal mass of quartz sand, moistened with distilled water, and transferred to 50 mL incubation vessels (polypropylene syringes). The bottom was layered with 6 mm glass wool, covered with 3 mm glass wool and 10 g quartz sand to prevent soil particle splashing during leaching. The assembly was gently tapped to ensure uniform packing.

Soils were leached four times with 100 mL of 0.01 $\mathrm{mol \cdot L^{-1}}$ $CaCl_2$ solution, and leachates were collected for ammonium and nitrate analysis. Twenty-five milliliters of N-free nutrient solution (0.002 $\mathrm{mol \cdot L^{-1}}$ $CaSO_4 \cdot 2H_2O$, 0.002 $\mathrm{mol \cdot L^{-1}}$ $MgSO_4$, 0.005 $\mathrm{mol \cdot L^{-1}}$ $Ca(H_2PO_4)_2 \cdot 2H_2O$, 0.0025 $\mathrm{mol \cdot L^{-1}}$ K_2SO_4) was then added, and the soil was filtered under vacuum (-80 kPa) to remove excess water. Vessels were sealed with Parafilm and incubated at 35°C. Leaching was repeated at weeks 0, 1, 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24, 26, 28, and 30 using the same procedure. Leachate NO_3^--N and NH_4^+-N concentrations were determined by continuous flow analyzer (Bran+Luebbe AA3, Germany). Cumulative N mineralization was calculated as the sum of mineralized N across all incubation periods.

The single-factor exponential model for soil N mineralization:

$$N_t = N_0(1 - e^{-kt})$$

where N_t is cumulative N mineralization at time t ($\mathrm{mg \cdot kg^{-1}}$), N_0 is the N mineralization potential ($\mathrm{mg \cdot kg^{-1}}$) representing mineralizable N, k is the mineralization rate constant, and t is incubation time (days).

1.3 Analytical Methods

Soil organic matter, total N, available P, and available K were determined using conventional analytical methods. After incubation, soil mineral N was extracted with 1 mol · L^{-1} KCl and analyzed for $NH_4{}^+$-N and $NO_3{}^-$-N using continuous flow analyzer. Plant shoots and roots from each harvest were dried, ground to pass a 0.2 mm sieve, digested with H_2SO_4-H_2O_2, and analyzed for total N by semi-micro Kjeldahl method.

1.4 Data Processing and Analysis

Data were analyzed using SAS 8.0 for ANOVA, correlation analysis, and significance testing. Figures were prepared using SigmaPlot 12.0.

2.1 Effects of Cultivation Year on Tomato Growth

As shown in , plant height and stem diameter increased continuously with growth duration across all treatments, with values consistently ranking 3 years > 2 years > 0 years. Except for plant height at 20 days after transplanting in the first harvest, all growth parameters in 2- and 3-year greenhouse soils were significantly higher than pre-construction soils ($P<0.05$), though differences between 2- and 3-year treatments were not significant.

Within the same cultivation duration, growth indices varied substantially among harvests. For the 0-year treatment, chlorophyll content at 20 days was significantly lower in the third harvest than in the first two ($P<0.05$), while plant height and stem diameter showed no significant differences among harvests. At 35 days, the third harvest showed significantly greater plant height but lower chlorophyll content compared to earlier harvests ($P<0.05$), with no significant difference in stem diameter. At 50 days, only chlorophyll content differed significantly (third harvest < second harvest).

For the 2-year treatment, plant height at 20 days was significantly lower in the first harvest than in subsequent harvests, while chlorophyll content was highest in the second harvest. At 35 and 50 days, no significant differences were observed among harvests. In the 3-year treatment, plant height and stem diameter at 20 days were significantly lower in the first harvest, while chlorophyll content was highest in the second harvest. At 35 days, plant height was lower in the first harvest and chlorophyll content was lower in the third harvest, with no difference in stem diameter. At 50 days, stem diameter and chlorophyll content were significantly lower in the third harvest.

Biomass accumulation increased with cultivation duration. Aboveground and root biomass in 2- and 3-year treatments were significantly higher than in the 0-year treatment ($P>0.05$ for 2- vs 3-year comparison). The 3-year treatment showed the greatest aboveground biomass, a 462.9% increase over the 0-year treatment, while the 2-year treatment increased by 409.1%. Root biomass increased by 61.4% and 105.3% in the 2- and 3-year treatments, respectively.

Within treatments, biomass varied among harvests. In the 0-year treatment, aboveground biomass in the first and second harvests was 3.9 and 3.3 times that of the third harvest, respectively, while root biomass was 1.8 and 1.0 times greater. In the 2-year treatment, second-harvest aboveground biomass was 1.5 and 3.8 times that of the first and third harvests, respectively. In the 3-year treatment, second-harvest aboveground biomass was 1.9 and 5.3 times greater than the first and third harvests, with all differences being significant. Root biomass did not differ significantly among harvests in either the 2- or 3-year treatments.

2.2 Effects of Cultivation Year on Tomato N Content and Uptake

As shown in , N concentrations in both shoots and roots were higher in longer-cultivated greenhouses. In the first harvest, shoot N concentration was 1.29% in the 0-year treatment, compared to 1.17 and 1.27 times higher in the 2- and 3-year treatments, respectively. Root N concentration was 0.42% in the 0-year treatment, increasing to 1.91 and 2.07 times higher in the 2- and 3-year treatments. Across all three harvests, shoot and root N concentrations in the 2- and 3-year treatments were significantly higher than in the 0-year treatment, though differences between the 2- and 3-year treatments were not significant ($P>0.05$).

Total N uptake ranged from 28.9 to 251.5 $\mathrm{mg \cdot pot^{-1}}$. Cumulatively, the 2- and 3-year treatments showed 6.0- and 8.7-fold increases over the 0-year treatment ($P<0.05$). The 3-year treatment had higher N uptake than the 2-year treatment, but the difference was not significant ($P>0.05$). At each growth stage, N uptake in the 2- and 3-year treatments was significantly higher than in the 0-year treatment, increasing with cultivation duration, though differences between the 2- and 3-year treatments were not significant.

Within treatments, shoot N concentration in the 0-year treatment was 1.4 and 1.6 times higher in the first harvest than in the second and third harvests, respectively. In contrast, the 2- and 3-year treatments showed highest shoot N concentrations in the second harvest. Root N concentrations were significantly lower in the first and third harvests compared to the second harvest across all treatments. For N uptake, the third harvest in the 0-year treatment was significantly lower than the first two harvests, while the 2- and 3-year treatments showed significantly higher N uptake in the second harvest compared to the first and third.

2.3 Effects of Cultivation Year on Soil Nutrients, Mineral N, and Mineralizable N

As shown in , soil organic matter in the 0–20 cm layer increased by 62.1% and 131.0% after 2 and 3 years of cultivation, respectively ($P<0.01$). Total N content increased significantly after 3 years, rising 67.1% above pre-construction levels. Soil mineral N, available P, and available K also increased significantly after 3 years, with average increases of 621.4%, 1445.6%, and 146.9%, respectively.

Initial mineral N content was 13.07 $\mathrm{mg \cdot kg^{-1}}$ in the 0-year treatment, increasing by 409.10% and 621.42% in the 2- and 3-year treatments. Mineralizable N determined by long-term aerobic incubation was 41.4 $mg \cdot kg^{-1}$ in the 0-year treatment, increasing significantly to 2.84 and 2.96 times higher in the 2- and 3-year treatments. Tomato N uptake, initial mineral N, and mineralizable N all increased significantly in the 2- and 3-year treatments compared to the 0-year treatment ($P<0.05$).

To accurately evaluate soil N supply capacity, correlations were analyzed between tomato N uptake and initial mineral N, total N, organic matter, and cumulative mineralized N. As shown in [Figure 1: see original paper], highly significant positive correlations were observed ($P<0.01$), with correlation coefficients of 0.857, 0.854, 0.933, and 0.886, respectively. The strongest correlation was between cumulative mineralized N and tomato N uptake, indicating that soil N supply depends on the magnitude of initial mineral N, total N, and organic matter content.

3.1 Effects of Cultivation Year on Greenhouse Soil N Supply Capacity

This study demonstrated that tomato growth parameters (height, stem diameter, above- and below-ground biomass, and chlorophyll content) increased with cultivation duration, associated with higher soil organic matter, total N, and available nutrient contents in longer-cultivated greenhouses. Both tomato N uptake measured by pot depletion and soil mineralizable N measured by intermittent leaching increased significantly. Enhanced N uptake with cultivation years is attributable to substantial organic manure applications that increase soil organic matter and total N. Survey data from over 170 greenhouses in the study area revealed average manure application rates of 142 $t \cdot hm^{-2}$ (range: 36–360 $t \cdot hm^{-2}$), with 62% of greenhouses receiving >120 $t \cdot hm^{-2}$. Even higher rates (177-265.1 $t \cdot hm^{-2}$) have been reported in Shandong, a region with longer greenhouse cultivation history. Long-term heavy manure application significantly increases soil organic matter and total N content. Our results showed organic matter concentrations of 8.7-20.1 $g \cdot kg^{-1}$ in the 0–20 cm layer, increasing with cultivation years. Zhou' s N depletion experiments similarly demonstrated that manure application markedly enhances greenhouse soil N supply. Thus, long-term fertilization, particularly organic amendments, substantially improves the soil organic N pool and N supply capacity. Consequently, chemical N fertilizer rates should be reduced as greenhouse cultivation years increase.

While this study clearly shows enhanced soil N supply capacity during the first three years of greenhouse cultivation, further research is needed to characterize long-term trends beyond this initial period. Additionally, field conditions differ substantially from incubation experiments in terms of temperature and moisture regimes, necessitating field trials to quantitatively determine appropriate reductions in chemical N fertilizer rates.

3.2 Evaluation Methods for Soil N Supply Capacity

Crop N uptake derives from both inorganic N present at planting and N mineralized during growth. Comprehensive assessment of soil N supply capacity must therefore consider both initial mineral N and mineralization during the growing period. Since mineralizable N is closely related to soil organic matter and total N, measuring these parameters provides a simple evaluation approach. Both biological depletion and long-term intermittent leaching are classical methods for assessing soil N supply, with the former being the most direct. This study employed both methods to evaluate N supply capacity across cultivation years. Results showed highly significant positive correlations between tomato N uptake and soil organic matter, total N, initial mineral N, and cumulative mineralized N, confirming their utility as indicators of soil N supply capacity.

Conclusion

With increasing cultivation years in newly built solar greenhouses, tomato growth indices (height, stem diameter, and chlorophyll content) increased progressively. Soil organic matter, total N, and available nutrient contents after three years were significantly higher than pre-construction levels. Tomato N uptake and soil mineralizable N increased substantially, indicating significantly enhanced soil N supply capacity. Therefore, chemical N fertilizer application rates should be reduced in older greenhouses. Soil organic matter, total N, initial mineral N, and cumulative mineralized N were all highly significantly correlated with tomato N uptake, with mineralizable N showing the strongest relationship, demonstrating their effectiveness for evaluating soil N supply capacity.

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