EFFECTS OF THE COUPLING OF MICROBIAL FERTILIZERS AND CHEMICAL NITROGEN FERTILIZERS ON GREENHOUSE TOMATO (*SOLANUM LYCOPERSICUM* L.) GROWTH AND YIELD

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Abstract. The impact of the coupling of microbial fertilizers and chemical nitrogen fertilizers on greenhouse tomato is unclear. This study used a completely randomized experimental design to explore the effects of different bacterial application levels (B, B1: 0 times, B2: 1 time, B3: 2 times the standard bacterial application amount) and nitrogen application levels (N, N1: 0.3 times, N2: 0.6 times, N3: 0.9 times, N4: 1.2 times the standard nitrogen application levels) on the growth, quality and yield of greenhouse tomatoes. The results showed that with the increase of B, the photosynthetic rate, leaf area index, plant height, stem diameter, root morphology development and dry matter mass of greenhouse tomato increased first and then decreased; the increase of N also showed a similar trend. The quality of fruit increased first and then decreased with the increase of B and N. The B2N3 combination treatment performed the best in terms of quality. With the increase of B and N, the tomato yield increased first and then decreased. The comprehensive benefit evaluation of TOPSIS method further confirmed that B2N3 treatment was superior to other treatments. Therefore, it is recommended to adopt the B2N3 combined B and N mode in greenhouse tomato cultivation.

Keywords: *coupling effect, fruit quality, nitrogen use efficiency, economic benefits, comprehensive evaluation*

Introduction

Greenhouse is the development direction of modern agriculture and one of the important signs of agricultural modernization. The relatively closed crop growth environment in greenhouses, achieved through physical structures (such as transparent covering materials) that isolate the internal conditions from external natural factors, enables artificial regulation of climatic parameters (temperature, humidity, light) while minimizing biological interference and extreme weather impacts, with soil nutrient replenishment primarily dependent on artificial supplementation (Zhang et al., 2022). Due to the rapid growth of greenhouse tomato *(Solanum lycopersicum* L.*)*, the soil shows the characteristics of high nitrogen demand. Therefore, measuring the level of nitrogen fertilizer utilization in greenhouse has become a hot topic in current research (Tarrass et al., 2023; Calderon et al., 2025).The study found that too low nitrogen application rate could not meet the growth of tomato, leading to a significant reduction in yield. Excessive nitrogen application can lead to the destruction of soil aggregate structure and cause soil hardening, soil acidification, hindering the exchange of gas between soil pores in the root zone of tomato and the ability of nutrient activation to be absorbed by roots. It can also

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cause a series of problems such as waste of resources, environmental pollution, low yield and quality decline of crops (Chai et al., 2023; Chojnacka et al., 2023; Wen et al., 2023). At present, a large amount of nitrogen fertilizer is widely used in greenhouse (Liu et al., 2023; Ma et al., 2025). In the face of the practical problems faced by agricultural development, we cannot guarantee the ecological environment by sacrificing crop yield by reducing the use of nitrogen fertilizer, nor increase tomato yield by increasing the use of nitrogen fertilizer unilaterally and significantly regardless of environmental quality. How to find a way to ensure the sustainable development of nitrogen fertilizer use that can not only ensure the continuous increase of crop tomato, but also maintain a good ecological environment is an urgent problem to be solved. Optimizing soil microbial community is one of the important breakthroughs to promote tomato fertilizer saving, yield increasing and environmental protection after traditional optimized nitrogen fertilizer management.

There are many ways to optimize the structure of soil microbial community, among which adding beneficial microbial agents directly to soil is one of the most direct, rapid and effective methods (Yu et al., 2022; Cui et al., 2023; Fu et al., 2025). The addition of soil microbial agents can improve the structure of soil aggregates, increase the frequency of soil ion exchange, and reduce the relative quality of soil, thereby increasing the contact rate between crops and soil organic matter. Microorganisms can form metabolism through life activities, effectively absorb the original harmful substances in the soil, form a new microbial system, improve the soil micro-environment, and reduce soil bacteria; at the same time, soil microorganisms can also increase the soil 's ability to retain carbon and nitrogen in the air, and also have a good role in dissolving phosphorus and potassium, which can convert the ineffective phosphorus and potassium in the soil into effective phosphorus and potassium (Ng et al., 2022; Chen et al., 2023; Meng et al., 2024; Garces et al., 2025). The study found that the addition of nitrogen-transforming bacteria to the soil improved the micro-ecological environment of the rhizosphere soil of tea trees and increased soil nutrients (Han et al., 2015). Microbial fertilizer has a good effect on improving soil microbial activity in dry-land area of Loess Plateau, which can increase the yield of dry-land oats (Tian et al., 2020). There was an interactive response relationship between barley roots and *Bacillus subtilis*, *Fusarium graminearum* (Reyna et al., 2023). Microbial agents can reduce soil NO_3^--N content by 22% -29%, reduce soil N_2O emissions by 58-73%, and reduce NH_3 volatilization by more than 13% (Zhang et al., 2021a). The rhizosphere bacteria inhibit greenhouse gas emissions from micro-plastic contaminated soil by regulating soil enzyme activity and microbial community structure (Khan et al., 2025).

At present, the purpose of reducing nitrogen fertilizer and increasing efficiency is mainly achieved through rational fertilization, tillage and mulching, and integration of water and fertilizer. However, there are few studies on regulating the soil by microbial means, enhancing the soil 's own nitrogen supply capacity, and excavating the space for nitrogen fertilizer reduction and efficiency from the inside of the soil. The introduction of beneficial microbial flora through soil enrichment technology to reduce the application of nitrogen fertilizer and improve the transformation and degradation of nitrogen in soil, so as to achieve a more effective nitrogen reduction mechanism (the coupling of microbial fertilizers and chemical nitrogen fertilizers) has not yet formed a complete theoretical system in the application of greenhouse. For example, the regulation of plant growth under different the coupling of microbial fertilizers and chemical nitrogen fertilizers is still unclear. The existence of the above problems limits our understanding of the mechanism of the coupling of microbial fertilizers and chemical nitrogen fertilizers in soil. In production practice, farmers pursue the high yield of greenhouse tomatoes, while consumers pay more attention to the quality of tomatoes. At the same time, improving the utilization efficiency of bacterial nitrogen is the key to the sustainable development of modern agriculture. Appropriate amount of enrichment and nitrogen reduction treatment can significantly increase the yield of tomato, but excessive application may lead to the decline of fruit quality and the decrease of bacterial nitrogen utilization efficiency, thus increasing the production cost and environmental pressure. However, it is a complex and challenging task to maintain or improve tomato quality and optimize bacterial nitrogen use efficiency while pursuing high yield. As a multi-objective decision analysis tool, TOPSIS method provides an effective solution for optimizing the enrichment and nitrogen reduction treatment of greenhouse tomatoes. This method has been widely used in agricultural comprehensive evaluation. By comprehensively considering the yield, quality and nitrogen utilization efficiency of tomatoes, the best treatment scheme can be selected (Luo and Li, 2018; Zhang et al., 2020; Xue et al., 2025).Although the application of TOPSIS method in greenhouse tomato irrigation management has been reported, it is still relatively less applied in the comprehensive evaluation of the coupling of microbial fertilizers and chemical nitrogen fertilizers (microbial fertilizers and chemical nitrogen fertilizers) technology. Therefore, in this study, greenhouse tomatoes were used as the research object to explore how the growth and yield of greenhouse tomatoes responded under different bacterial application levels and nitrogen application levels. In addition, TOPSIS method was used to construct a comprehensive benefit evaluation model for the growth of greenhouse tomatoes with enrichment of bacteria and reduction of nitrogen to optimize different treatments, and the best combination mode of bacterial application levels and nitrogen application levels was obtained. The purpose of this paper is to provide data support for fertilizer saving and yield increase of tomato in greenhouse through experiment and comprehensive benefit evaluation model, in order to explore an efficient, safe, resource-saving and environment-friendly green sustainable development model of modern agriculture.

Materials and methods

Experimental site and management

The experiment was conducted in a greenhouse in Chencao Township, Xuchang City, Henan Province, China (N 34°08′, E 113°59′). The greenhouse belongs to the northern temperate continental monsoon climate, with an altitude of 85.0 m. The average annual temperature is 14.3 °C, and the average annual rainfall is 640.9 mm. The precipitation from June to September accounts for more than 70% of the annual precipitation. The frost-free period is 220 days, and the annual sunshine time is about 2400 hours. The average bulk density of 1 m soil layer was 1.45 g/cm^3, and the field water holding capacity was 25.40% (weight water content). The soil was medium loam. The content of organic matter, total phosphorus, total potassium, total nitrogen, alkali-hydrolyzable nitrogen, available phosphorus and available potassium in the plough layer before sowing was 5.62 g/kg, 0.44 g/kg, 15.12 g/kg, 0.37 g/kg, 24.91 mg/kg, 23.89 mg/kg and 75 mg/kg, respectively. The tomato variety is ' *Nongbofenba 1316* ', which is planted on a ridge with one ridge and two rows. The row spacing of tomato is 50 cm, the plant spacing is 40 cm, and the spacing of each plot is 2.0 m. The field management measures such as fertilization, irrigation and spraying in each plot were consistent. The irrigation water comes from the groundwater in this area. In order to ensure the survival of seedlings on the day of planting, the irrigation water is unified with reference to the local tomato planting experience.

Experimental design

In this study, the bacterial application levels and nitrogen application levels were set as two factors. Among them, the bacterial application levels (B) was set up at three levels, which were 0 times the standard enrichment amount (*Bacillus subtilis*+*Trichoderma harzianum*=0+0 kg/ha/time, B1), 1 times the standard enrichment amount (*Bacillus subtilis*+*Trichoderma harzianum*=4+3 kg/ha/time, B2), 2 times the standard enrichment amount (*Bacillus subtilis*+*Trichoderma harzianum*=8+6 kg/ha/time, B3), and the bacteria were applied every 10 days for a total of 10 times, using the water-bacteria integration model. The nitrogen application levels (N) was based on the standard nitrogen application rate of local planting experience. Four levels were set up, which were 0.3 times the standard nitrogen application rate (7 kg/ha/time, N1), 0.6 times the standard nitrogen application rate (14 kg/ha/time, N2), 0.9 times the standard nitrogen application rate (21 kg/ha/time, N3), and 1.2 times the standard nitrogen application rate (28 kg/ha/time, N4). Nitrogen was applied every 10 days for a total of 10 times. In this study, the water-bacteria integration model was used to apply bacteria and fertilizer. The irrigation schematic diagram is shown in *Figure 1*.

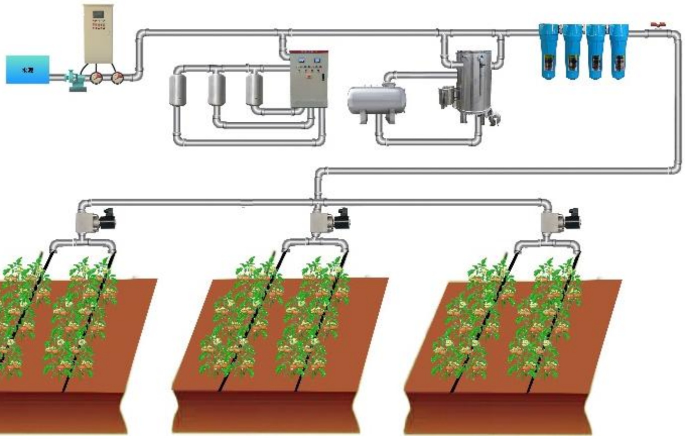

Figure 1. *Irrigation schematic diagram of drip irrigation water bacteria nitrogen integration technology*

The experiment was carried out in the greenhouse of Xuchang Irrigation Experimental Station in Henan Province from March 20, 2023 to July 25, 2023 and from March 22, 2024 to July 20, 2024.In 2023, the tomato was planted on March 20, 2023, and the experimental treatment was started on March 27, 2023. On July 05, 2023, the last irrigation was applied with bacterial fertilizer. The tomato was fully harvested on July 15, 2023. Tomato in 2024 was planted on March 22, 2024, experimental treatment began on March 29, 2024. On July 07, 2024, the last irrigation was applied with bacterial fertilizer. The tomato was fully harvested on July 17, 2024. In this study, a total of 12 treatments (*Table 1*), each treatment was repeated three times, a total of 36 experimental plots. The irrigation amount was controlled on the basis of the cumulative evaporation from a 20-cm diameter standard pan (Epan, DY.AM3, Weifang Dayu Hydrology Technology Co., Ltd., Shandong, China) (Zhang et al., 2021b). The evaporation amount was measured at 08:00

am every 5 d. The irrigation amount was evaluated after the measurement. The of irrigation quota was calculated according to the reference (Zhang et al., 2021b) was used to calculate the irrigation amount. The meteorological data outside the greenhouse during the growth period of greenhouse tomatoes are shown in *Figure 2*. This data is only used as an environmental background reference and does not affect the control of experimental variables.

Table 1. *Test scheme*

No.	**Treatment**	**Bacterial application levels (*Bacillus subtilis*+*Trichoderma harzianum*) kg/ha/growth period**	**Nitrogen application levels kg/ha/growth period**	**Irrigation amount mm**	
				2023	**2024**
1	B1N1	0.00	70	303.10	334.29
2	B1N2	0.00	140		
3	B1N3	0.00	210		
4	B1N4	0.00	280		
5	B2N1	40+30	70		
6	B2N2	40+30	140		
7	B2N3	40+30	210		
8	B2N4	40+30	280		
9	B3N1	80+60	70		
10	B3N2	80+60	140		
11	B3N3	80+60	210		
12	B3N4	80+60	280		

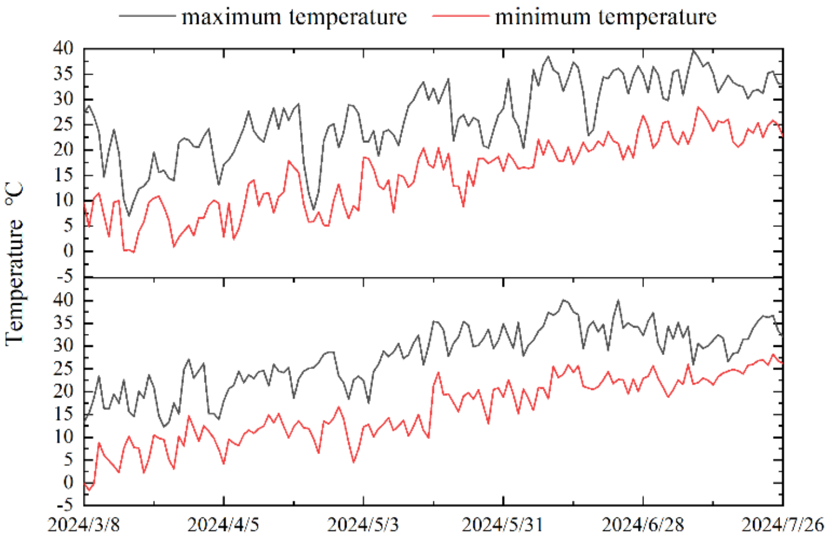

Figure 2. *Meteorological data of greenhouse tomato growth period*

Measurements and computational methods

Photosynthesis

Three healthy conjoined leaves with sufficient light and consistent leaf position were randomly selected, and the gas exchange parameters such as net photosynthetic rate (P*n*) were measured by LC Pro-SD automatic portable photosynthesis instrument. The open gas path was used in the measurement, and the CO_2 gas was collected from a relatively stable 2-3 m air. The light intensity was set at 800 μmol/m^2·s, and the flow rate was set at 500 μmol/s. The determination was carried out at 9: 00-11: 00 on 20,50,80 and 110 days after planting (Zhang et al., 2022).

Growth

The growth-related indices were measured at 20,50,80,110 days after planting, and 3 plants were randomly selected from each plot; Plant height(PHT): ruler measurement; Stem diameter(SDT): measured with electronic vernier caliper at the base stem; Leaf area indices(LAI): measured by AccuPARLP-80 canopy analyzer (Decagon Devices, Inc., Pullman, Wash. USA).

The root morphological structure and dry matter accumulation of tomato

On the 20, 50, 80 and 110 day of tomato planting, 6 tomato plants were randomly selected in each plot to cut all the above-ground parts, and the roots of the plants were obtained by digging a pit with a diameter of about 0.2 m and a depth of about 0.4 m centered on the stems of the plants. Carefully shake off the rhizosphere soil and pick up the residual roots to slowly rinse the soil with small water flow. During the washing, the roots and soil were placed on a 150-mesh steel sieve to minimize root loss. The roots of three tomato plants were scanned by Epson Perfection V700 scanner to obtain TIF images. Finally, the TIF images were processed by WinRHIZO Pro software to obtain the total root length, total number of root tips and bifurcation number of greenhouse tomatoes. The root activity of tomato was determined by triphenyltetrazolium chloride method. The stems, leaves, fruits and roots of the remaining three tomatoes were placed in an oven at 105 °C for 15 min and dried to constant weight at 75 °C (Zhang et al., 2022, 2023a).

Quality

In the mature period of tomato, three tomato fruits were randomly selected from each plot for determination, and the single fruit was homogenized to determine the flavor and nutritional indexes of the fruit. Fruit shape (weight of single fruit (WSF), vertical diameter of single fruit (WDSF), transverse diameter of single fruit (TDSF)), flavor index (total soluble solids content (TSOC), total soluble sugar content (TSUC), sugar/acid ratio (SA)), nutritional index (total soluble protein content (TSPC), vitamin C content (VCC), lycopene content (LC)) determination method refers to the literatures (Zhang et al., 2020).

Yield and bacterial nitrogen partial factor productivity

Yield (Zhang et al., 2022): Three tomatoes were randomly selected, and the mature fruit quality of four tomatoes was weighed by 0.01 g electronic scale, and the yield per hectare was converted.

Bacterial nitrogen partial productivity (Zhang et al., 2022): calculated by *Formula 1.*

$$\mathrm{BNPP} = \mathrm{Y}/(\mathrm{B} + \mathrm{N}) \qquad \text{(Eq.1)}$$

In the formula: BNPP represents the bacterial nitrogen partial productivity, kg/kg; Y represents the tomato fruit yield, kg/hm^2; B represents the bacterial application levels during the growth period of tomato, kg/hm^2; N represents the nitrogen application levels during the growth period of tomato, kg/hm^2.

Data analysis

Basic data analysis

Firstly, normality tests were performed on the experimental group data. Subsequently, one-way analysis of variance (ANOVA) was conducted using SPSS 22.0 (IBM Corp., Armonk, NY, USA). When significant main effects or interactions were detected ($P \le 0.05$), post hoc comparisons were performed using Tukey's Honestly Significant Difference (HSD) test to identify specific differences among treatment combinations and different levels of each factor. The significance threshold was uniformly set a $\alpha = 0.05$. Graphical representations were created using Origin Pro 2019 (OriginLab Corporation, Northampton, MA, USA). Unless otherwise specified, data in figures and tables are presented as mean±standard deviation. Univariate power estimation analysis in SPSS 22.0 was employed to determine the relative contribution rates of single factors or factor interactions.

Logistic growth curve equation

The Logistic growth curve equation of total dry matter mass of tomato was fitted by biostatistical method (Díaz-Pérez et al., 2018). The Logistic growth curve is an elongated S-shaped curve, which has a wide range of adaptability to the description of animal and plant growth processes. The Logistic equation is:

$$\mathrm{y} = \frac{\mathrm{a}}{1+e^{b-ct}} \tag{Eq.2}$$

$$\mathrm{t}_1 = \frac{\mathrm{b}-\ln(2+\sqrt{3})}{\mathrm{c}} \tag{Eq.3}$$

$$\mathrm{t}_1 = \frac{\mathrm{b}+\ln(2+\sqrt{3})}{\mathrm{c}} \tag{Eq.4}$$

$$\mathrm{LGD} = \mathrm{t}_2 - \mathrm{t}_1 \tag{Eq.5}$$

$$\mathrm{MGR} = \frac{\mathrm{ac}}{4} \tag{Eq.6}$$

$$\mathrm{LGR} = \frac{\mathrm{ac}}{2\sqrt{3}(2+\sqrt{3})} \tag{Eq.7}$$

$$\mathrm{TLG} = \frac{\mathrm{a}}{\sqrt{3}} \tag{Eq.8}$$

$$\mathrm{R}^2 = \frac{\sum_{i=1}^{N}(W_{Li}-W)^2}{\sum_{i=1}^{N}(W_{Ri}-W)^2} \tag{Eq.9}$$

In the formula: y is the total dry matter weight of tomato, g/plant; t is the number of days after tomato planting, d; a, b and c are the model coefficients; the predicted value of total dry matter weight of tomato, g/plant; the measured value of total dry matter weight of tomato, g/plant; the average value of the measured value of the total dry matter mass of tomato, g/plant; N is the number of samples.

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Comprehensive evaluation method

(1) Selection of evaluation index

The evaluation indexes mainly include three indexes: total dry matter quality, fruit quality, yield and bacterial nitrogen partial productivity of tomato. Among them, fruit quality quality indexes: WSF, WDSF, TDSF, TSOC, TSUC, SA, TSPC, VCC, LC were used as evaluation variables of tomato fruit quality indexes.

(2) Standardization and chemotaxis of raw data

Firstly, the data are standardized to eliminate the dimensional influence. Secondly, the data are processed with the same chemotaxis to ensure that the evaluation indicators are in the same direction. The specific calculation method refers to the literatures (Wu et al., 2018)

(3) Principal component analysis

SPSS 22.00 was used for principal component analysis, and the specific calculation method referred to literatures (Li et al., 2016). Finally, the comprehensive score of tomato quality was obtained as a parameter to measure the quality.

(4) Construction of TOPSIS comprehensive benefit evaluation model

TOPSIS comprehensive evaluation was carried out with tomato total dry matter quality, fruit quality comprehensive score, yield, bacterial nitrogen partial productivity and net income as comprehensive consideration indicators. Among them, the quality index PCA comprehensive score was used as the quality comprehensive response. The specific calculation method refers to the literatures (Zhang et al., 2020).

Results

Effects of different treatments on photosynthetic rate and leaf area index of greenhouse tomato leaves

Photosynthetic rate (Pn)

It can be seen from *Table 2* that with the advancement of greenhouse tomato growth period, the P*n* of greenhouse tomato leaves increased first and then decreased. The bacterial application levels (B) and nitrogen application levels (N) had significant effects on the P*n* of greenhouse tomato leaves ($P \leq 0.05$), and the relative contribution of B to the P*n* of tomato leaves was up to 25.20% and 54.10%. The relative contribution of N to the P*n* of tomato leaves was up to 20.60% and 54.60%.

When the N was constant, the B increased from B1 to B3, resulting in the P*n* of tomato leaves in each treatment increased first and then decreased. The P*n* of tomato leaves of B2 was about 19.72% and 14.85% higher than that of B1 treatment (the average growth period, the same below); it was also higher than that of B3 treatment by about 14.30% and 10.55%. When the B was constant, the N increased from N1 to N4, resulting in the P*n* of tomato leaves in each treatment increased first and then decreased, and the P*n* of tomato leaves of N3 was about 23.22% and 19.23% higher than that of N1 treatment. It was about 10.47% and 6.91% higher than that of N2 treatment. It was also higher than that of N4 treatment by about 6.03% and 5.71%.

Leaf area index (LAI)

It can be seen from *Table 3* that with the advancement of greenhouse tomato growth period, the LAI of greenhouse tomato increased first and then decreased. The two factors of B and N had significant effects on the LAI of greenhouse tomato (P≤0.05), and the relative contribution of B to tomato LAI was up to 31.50% and 32.10%. The relative contribution of N to tomato LAI was up to 23.40% and 32.70%.

Table 2. *Effects of microbial fertilizers and chemical nitrogen fertilizers on Pn of greenhouse tomato leaves*

	Treatment	**P*n***			
		20 d	**50 d**	**80 d**	**110 d**
2023	B1N1	12.07±1.41d	15.1±2.78c	16.88±3.04e	14.23±3.02d
	B1N2	13.46±1.56cd	16.84±3.11bc	18.84±3.4cde	15.91±3.36bcd
	B1N3	15.55±1.5ab	21.19±3.2a	23.45±4.52ab	19.47±3.45ab
	B1N4	13.97±1.58bc	18.22±4.85abc	21.95±2.73abc	18.45±3.84abc
	B2N1	15.2±1.39ab	20.04±5.3ab	23.82±2.95ab	20.34±3.41a
	B2N2	15.73±1.46ab	20.79±5.53ab	24.69±3.07ab	21.05±3.52a
	B2N3	15.39±2.22ab	22.41±3.06a	25.63±2.75a	21.38±4.82a
	B2N4	16.22±2.21a	21.52±2.38a	24.97±4.06ab	20.73±2.44a
	B3N1	12.73±1.21cd	14.89±3.56c	17.98±3.55de	14.98±3.76cd
	B3N2	15.5±1.44ab	18.14±4.27abc	21.87±4.45abc	18.35±4.56abc
	B3N3	16.39±1.9a	19.73±4.4ab	23.71±3.87ab	20±2.99a
	B3N4	15.41±2.46ab	18.42±3.46bc	21.22±3.55bcd	19.33±3.3ab
	F-value				
	B	10.874**	8.763**	16.198**	10.946**
	N	9.765**	5.86**	8.31**	5.57**
	B*N	2.218*	0.499ns	2.854*	0.997ns
2024	B1N1	13.07±0.43f	17.39±1.38f	17.83±1.01f	16.14±2.65d
	B1N2	14.64±0.47e	19.44±1.51e	19.95±1.12e	18.04±2.97bc
	B1N3	16.1±0.64bcd	21.64±1.53bcd	24.19±1.72abc	20.87±2.31a
	B1N4	15.5±0.61de	20.82±1.68de	23.3±1.15cd	19.61±2.55ab
	B2N1	16.53±1.09abcd	22.16±1.62bcd	24.73±1.49abc	19.91±0.65ab
	B2N2	17.13±1.14ab	23±1.68ab	25.18±1.29ab	20.61±0.65a
	B2N3	17.6±0.82a	24.16±1.62a	25.63±1.57a	21.09±1.52a
	B2N4	16.96±0.59abc	22.74±1.29abc	24.77±1.64abc	20.68±1.82a
	B3N1	13.32±1.61f	17.67±1.37f	19.42±1.52e	16.38±0.75cd
	B3N2	16.18±1.95bcd	21.53±1.67bcd	23.62±1.75bcd	19.93±0.9ab
	B3N3	16.91±1.04abc	22.49±1.46bcd	25.34±2.13a	19.78±1.39ab
	B3N4	15.83±1.36cd	21.24±2.07cd	22.21±1.52d	18.31±1.67b
	F-value				
	B	39.809**	38.603**	56.463**	13.478**
	N	27.028**	25.515**	38.411**	13.61**
	B*N	3.351**	2.642*	10.278**	2.769*

When the N was constant, the B increased from B1 to B3, resulting in the LAI of tomato in each treatment increased first and then decreased, and the LAI of B2 tomato was higher than that of B1 treatment by about 20.05% and 11.58% (mean growth period, the same below). It was also higher than that of B3 treatment by about 22.38% and 16.53%. When the B was constant, the N increased from N1 to N4, resulting in the LAI of tomato leaves in each treatment increased first and then decreased, and the LAI of tomato in N3 treatment was higher than that of N2 treatment by about 22.10% and 18.75%. It was also higher than that of N2 treatment by about 9.82% and 6.37%; it was also higher than that of N4 treatment by about 4.29% and 5.39%.

Table 3. *Effects of microbial fertilizers and chemical nitrogen fertilizers on LAI of greenhouse tomato leaves*

	Treatment	**LAI**			
		20 d	**50 d**	**80 d**	**110 d**
2023	B1N1	1.06±0.17de	2.28±0.39c	5.51±1.06e	4.98±0.74e
	B1N2	1.29±0.22abc	2.79±0.48abc	6.7±1.28bcde	6.07±0.88cde
	B1N3	1.41±0.23a	3.55±1.36a	7.18±0.73abc	7.41±1.34ab
	B1N4	1.18±0.28bcd	2.81±0.71abc	7.05±1.31abcd	6.39±0.92bcd
	B2N1	1.31±0.19abc	3.34±1.04ab	7.6±1.22abc	7.53±1.29ab
	B2N2	1.35±0.18abc	3.46±1.07a	7.87±1.27ab	7.8±1.33a
	B2N3	1.29±0.16abc	3.02±0.25abc	8.15±1.06a	7.61±0.56ab
	B2N4	1.4±0.22ab	3.57±0.8a	7.91±1.01ab	8±1.83a
	B3N1	0.93±0.16e	2.42±0.95bc	5.87±1.11de	4.95±1.07e
	B3N2	1.03±0.19de	2.7±1.06abc	6.56±1.22cde	5.51±1.18de
	B3N3	1.29±0.29	3.07±0.68abc	7.24±1.43abc	7.14±1.15abc
	B3N4	1.16±0.2cd	2.82±0.76abc	6.78±1.28bcd	6.9±1.07abc
	F-value				
	B	11.429**	4.955**	13.972**	22.118**
	N	5.426**	2.865*	5.067**	9.792**
	B*N	2.240*	1.552ns	0.548ns	2.4*
2024	B1N1	1.09±0.12d	2.52±0.43bc	5.84±0.78d	5.19±0.6e
	B1N2	1.32±0.14ab	3.07±0.52ab	7.13±0.94abc	6.31±0.77bcd
	B1N3	1.31±0.16ab	3.31±0.72a	7.66±1.03ab	6.61±0.61abc
	B1N4	1.21±0.11bcd	2.89±0.49ab	6.91±0.88bc	6.16±0.33bcd
	B2N1	1.31±0.1ab	3.23±0.6a	7.59±1.12ab	6.46±0.57abc
	B2N2	1.36±0.1ab	3.34±0.63a	7.84±1.15ab	6.7±0.59ab
	B2N3	1.38±0.11a	3.18±0.61a	8.05±0.85a	6.98±0.47a
	B2N4	1.39±0.19a	3.28±0.58a	7.75±1.13ab	6.63±0.57abc
	B3N1	1.13±0.19cd	2.23±0.46c	5.83±0.77d	5.13±0.48e
	B3N2	1.26±0.2abc	2.49±0.52bc	6.52±0.84cd	5.73±0.55d
	B3N3	1.36±0.16ab	3.02±0.6ab	7.27±0.98abc	6.31±0.65bcd
	B3N4	1.36±0.13ab	2.92±0.6ab	6.99±1.18abc	6.07±0.6cd
	F-value				
	B	7.078**	9.714**	13.955**	22.683**
	N	7.828**	3.896*	7.398**	15.525**
	B*N	1.361ns	2.569*	1.042ns	1.656ns

Effects of different treatments on plant height and stem diameter of greenhouse tomato

Plant height of tomato (PHT)

It can be seen from *Table 4* that with the advancement of greenhouse tomato growth period, the PHT of greenhouse tomato increased first and then decreased. The B and N had significant effects on the PHT of greenhouse tomato ($P \leq 0.05$), and the relative contribution of B to the PHT of tomato was up to 25.20% and 54.10%. The relative contribution of B to the PHT of tomato was up to 20.60% and 54.60%.

When the N was constant, the B increased from B1 to B3, resulting in the PHT of tomato in each treatment increased first and then decreased. The tomato PHT of B2 was higher than that of B1 treatment by about 18.44% and 17.98% (the average growth period, the same below); it was also higher than that of B3 treatment by about 5.15% and 6.41%.

When the B was constant, the N increased from N1 to N4, resulting in the PHT of tomato in each treatment increased first and then decreased, and the tomato PHT of N3 was higher than that of N1 treatment by about 46.18% and 45.15%. It was higher than that of N2 treatment by about 18.95% and 18.61%. It was also higher than that of N4 treatment by about 4.95% and 4.89%.

Table 4. *Effects of microbial fertilizers and chemical nitrogen fertilizers on PHT of greenhouse tomato*

	Treatment	**PHT**			
		20 d	**50 d**	**80 d**	**110 d**
2023	B1N1	28.64±0.95g	72.73±5.12g	77.78±4.58i	90.53±3.53g
	B1N2	36.89±2.05e	90.66±3.7d	106.41±3.58h	104.83±4.66f
	B1N3	42.57±2.25c	112.68±3.79b	135.99±4.21d	128.27±4.45d
	B1N4	36.53±1.54e	106.05±4.61c	131.12±5.08e	122.23±5.34e
	B2N1	35.95±1.51e	82.79±3.12e	112±5.01g	105.7±7.26f
	B2N2	41.32±1.92c	103.42±4.77c	139.44±5.44cd	131.1±3.66cd
	B2N3	53.74±2.35a	118.12±3.93a	149.71±3.96a	155.13±6.16a
	B2N4	51.44±2.28b	111.98±2.63b	144.47±3.67b	150.12±8.16a
	B3N1	32.47±1.85f	77.19±3.71f	102.72±4h	107.74±2.42f
	B3N2	39.55±1.6d	92.78±3.83d	117.32±4.35f	134.53±5.42c
	B3N3	51.5±2.05b	110.23±3.39b	142.02±4.35bc	154.03±5.88a
	B3N4	50.32±1.76b	106.38±3.76c	135.66±4.83d	143.88±7.96b
	F-value				
	B	249.038**	50.512**	251.967**	211.340**
	N	430.934**	450.05**	555.491**	324.969**
	B*N	20.276**	2.578*	20.191**	3.855**
2024	B1N1	30.28±0.9g	74.24±5.22g	77.9±4.58i	95.99±3.51g
	B1N2	39.11±2.03e	92.61±3.82d	106.47±3.51h	110.28±4.79f
	B1N3	45.12±2.26c	115.02±3.9b	136.17±4.29d	141.95±4.49c
	B1N4	38.73±1.65e	108.2±4.68c	131.11±5.11e	135.84±5.43d
	B2N1	37.95±1.61e	84.48±3.1e	112.13±5.01g	119.12±7.34e
	B2N2	43.8±1.98c	105.63±4.92c	139.65±5.45cd	144.79±3.64bc
	B2N3	56.85±2.45a	120.63±4.02a	149.73±3.99a	160.94±6.28a
	B2N4	54.45±2.36b	114.38±2.59b	144.61±3.63b	155.86±8.21a
	B3N1	34.37±1.92f	78.82±3.82f	102.76±3.95h	113.37±2.41f
	B3N2	41.8±1.59d	94.79±3.81d	117.34±4.38f	140.25±5.4cd
	B3N3	54.52±2.06b	112.7±3.47b	142.02±4.48bc	159.84±5.93a
	B3N4	53.26±1.79b	108.65±3.9c	135.8±4.84d	149.59±8.03b
	F-value				
	B	264.257**	50.647**	251.019**	181.791**
	N	465.187**	456.210**	550.856**	322.782**
	B*N	21.575**	2.507*	20.161**	4.844**

Stem diameter of tomato (SDT)

From *Table 5*, it can be seen that with the advancement of greenhouse tomato growth period, the SDT of greenhouse tomato showed an increasing trend. The B and N had significant effects on the SDT of greenhouse tomato (P≤0.05), and the relative contribution of B to the SDT of tomato was up to 16.40% and 68.60%. The relative contribution of B to the SDT of tomato was up to 19.29% and 19.11%.

Table 5. *Effects of microbial fertilizers and chemical nitrogen fertilizers on SDT of greenhouse tomato*

	Treatment	**SDT**			
		20 d	**50 d**	**80 d**	**110 d**
2023	B1N1	5.76±0.21g	7.04±0.58h	6.75±0.29h	8.2±0.43g
	B1N2	7.44±0.37e	8.77±0.4e	9.06±0.39g	9.44±0.52f
	B1N3	8.67±0.5c	10.92±0.41b	11.61±0.31c	11.66±0.35de
	B1N4	7.49±0.38e	10.3±0.48d	11.15±0.42d	11.17±0.57e
	B2N1	7.35±0.3e	8.08±0.28f	9.6±0.42f	9.68±0.63f
	B2N2	8.47±0.38c	10.05±0.46d	11.87±0.45bc	11.95±0.28cd
	B2N3	10.93±0.49a	11.47±0.34a	12.61±0.38a	14.14±0.59a
	B2N4	10.48±0.48b	10.95±0.25b	12.22±0.33b	13.63±0.74a
	B3N1	6.69±0.42f	7.56±0.29g	8.81±0.39g	9.9±0.23f
	B3N2	8.08±0.3d	9.08±0.34e	10.12±0.32e	12.24±0.52c
	B3N3	10.44±0.34b	10.73±0.38bc	12.03±0.32b	13.93±0.54a
	B3N4	10.2±0.33b	10.39±0.43cd	11.55±0.38c	13.1±0.78b
	F-value				
	B	260.092**	48.888**	244.888**	199.399**
	N	423.879**	410.528**	541.5**	289.036**
	B*N	16.418**	2.381*	21.581**	3.221**
2024	B1N1	5.8±0.37g	7.37±0.67h	7.07±0.56h	8.87±0.4g
	B1N2	7.5±0.37e	9.24±0.48e	9.47±0.34g	10.18±0.44f
	B1N3	8.74±0.5c	11.39±0.42b	12.12±0.4c	12.51±0.38d
	B1N4	7.52±0.24e	10.74±0.47d	11.64±0.41d	11.95±0.54e
	B2N1	7.35±0.26e	8.47±0.3f	10.03±0.5f	10.49±0.68f
	B2N2	8.48±0.43cd	10.53±0.53d	12.52±0.45b	12.78±0.33cd
	B2N3	10.9±0.47a	11.97±0.4a	13.31±0.37a	15.05±0.64a
	B2N4	10.46±0.5b	11.36±0.23b	12.88±0.34b	14.62±0.75a
	B3N1	6.69±0.44f	7.93±0.31g	9.21±0.31g	10.63±0.26f
	B3N2	8.13±0.34d	9.5±0.38e	10.55±0.35e	13.23±0.54c
	B3N3	10.42±0.37b	11.18±0.39bc	12.69±0.39b	14.97±0.61a
	B3N4	10.22±0.39b	10.81±0.43cd	12.11±0.37c	14.01±0.69b
	F-value				
	B	226.918**	43.767**	242.961**	224.648**
	N	391.409**	367.365**	508.583**	315.711**
	B*N	15.227**	2.268*	18.622**	3.855**

When the N was constant, the B increased from B1 to B3, resulting in the SDT of tomato in each treatment increased first and then decreased. The tomato SDT of B2 was higher than that of B1 treatment by about 19.29% and 19.11% (the average growth period, the same below); it was also higher than that of B3 treatment by about 5.23% and 5.18%. When the B was constant, the N increased from N1 to N4, resulting in the SDT of tomato in each treatment increased first and then decreased, and the tomato SDT of N3 was higher than that of N1 treatment by about 45.81% and 45.38%. It was higher than that of N2 treatment by about 19.37% and 18.94%. It was also higher than that of N4 treatment by about 4.91% and 5.00%.

Effects of different treatments on root morphology of greenhouse tomato

It can be seen from *Table 6* that with the advancement of greenhouse tomato growth period, the root activity of root (RAR) increased first and then decreased, and the forks of root (FR), total length of root (TLR), total surface area of root (TSAR), total volume of root (TVR) and tip number of root (TNR) increased.

Table 6. *Effects of microbial fertilizers and chemical nitrogen fertilizers on root morphology of greenhouse tomato*

Index	**Treatment**	**2023**				**2024**			
		20	**50**	**80**	**110**	**20**	**50**	**80**	**110**
Root activity of root mg/g/h	B1N1	0.4±0.1d	1.24±0.17f	1.82±0.15e	1.42±0.05g	0.5±0.02e	1.28±0.04g	1.98±0.2e	1.6±0.21e
	B1N2	0.43±0.12cd	1.41±0.19ef	2.04±0.18d	1.82±0.1e	0.6±0.02d	1.65±0.09e	2.2±0.23e	1.99±0.26cd
	B1N3	0.63±0.14ab	1.59±0.27bcde	2.28±0.24c	2.11±0.11c	0.64±0.02	1.9±0.09c	2.57±0.18bcd	2.49±0.41b
	B1N4	0.56±0.14abcd	1.54±0.25cde	2.17±0.19cd	1.8±0.08e	0.64±0.03c	1.63±0.07e	2.55±0.23cd	1.97±0.39d
	B2N1	0.68±0.23a	1.87±0.38ab	2.6±0.16b	1.78±0.07e	0.7±0.04b	1.61±0.06e	2.69±0.12bcd	2.39±0.27c
	B2N2	0.69±0.24a	1.93±0.39a	2.69±0.17b	2.04±0.09c	0.71±0.04b	1.85±0.08c	2.78±0.12bc	2.47±0.28b
	B2N3	0.67±0.15ab	2±0.39a	2.9±0.12a	2.64±0.11a	0.75±0.02a	2.4±0.11a	3.05±0.16a	2.89±0.55a
	B2N4	0.66±0.21ab	2±0.19a	2.91±0.18a	2.54±0.11b	0.76±0.05a	2.3±0.1b	3.12±0.21a	3.09±0.85a
	B3N1	0.49±0.08bcd	1.48±0.22def	1.86±0.1e	1.61±0.09f	0.6±0.02d	1.45±0.08f	2.09±0.23e	2.02±0.22cd
	B3N2	0.6±0.1abc	1.8±0.27abc	2.25±0.11c	1.94±0.08d	0.65±0.03c	1.75±0.07d	2.53±0.29d	2.25±0.25bcd
	B3N3	0.68±0.18a	1.91±0.31a	2.64±0.26b	2.54±0.1b	0.67±0.06c	2.3±0.08b	2.81±0.21b	2.4±0.32c
	B3N4	0.61±0.19ab	1.73±0.28abcd	2.61±0.15b	2.48±0.09b	0.64±0.04c	2.24±0.07b	2.72±0.45bcd	2.35±0.21bcd
	F-value								
	B	9.368**	28.112**	147.288**	252.899**	145.614**	264.947**	58.112**	29.317**
	N	3.301*	5.492**	49.128**	438.807**	36.477**	460.316**	35.02**	12.106**
	B*N	1.267ns	0.647ns	4.092**	20.72**	5.443**	21.77**	1.217ns	2.073ns
Forks of root forks/plant	B1N1	186.39±45.25c	807.32±150.8g	1232.87±198.14f	1420.21±72.17f	210.78±7.09e	823.78±42.04f	1241.39±211.35d	1494.21±156.1e
	B1N2	209.02±49.87bc	908.6±167.5efg	1377.19±220.58ef	1724.68±73.66d	240.23±8.01d	1001.12±42.9d	1388.2±236.45cd	1821.26±184.61cd
	B1N3	226.62±47bc	975.97±193.73cdefg	1555.62±256.94de	2065.8±65.68c	243.45±5.37d	1199.78±38.26c	1522.53±202.11c	2205.49±336.95b
	B1N4	219.28±66.84bc	951.48±116.76defg	1530.13±144.35de	1989.37±73.53c	243.45±11.2d	1155.28±42.83c	1522.53±224.71c	2132.48±150.73bc
	B2N1	274.34±63.83ab	1136.29±186.74abc	1739.03±264.94bcd	1608.01±59.95e	256.67±6.9c	936.57±34.92e	1757.39±223.83b	2161.4±464.16b
	B2N2	284.05±66.12ab	1175.75±192.67ab	1801.05±273.44abc	2010.92±93.49c	266.09±7.15b	1171.24±54.45c	1821.81±229.58b	2236.22±481.95b
	B2N3	318.52±122.39a	1199.06±190.88a	1962.73±139.36a	2297.03±77.88a	281.23±11.75a	1337.88±45.37a	2033.77±110.7a	2681.92±320.27a
	B2N4	320.22±117.31a	1174.43±182.91ab	1932.87±235.65ab	2178.9±50.39b	280.01±12.3a	1269.07±29.34b	1995.98±123.98a	2701.13±512.16a
	B3N1	190.12±38.93c	848.09±104.7fg	1311.75±106.71f	1412.3±100.46f	217.48±5.81e	822.59±58.5f	1244.37±101.25d	1757.42±218.85de

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	B3N2	231.74±47.26bc	1030.72±129.87abcde	1602.95±131.83cd	1762.79±72.64d	264.6±6.94b	1026.72±42.31d	1519.47±127.08c	1932.94±243.91bcd
	B3N3	272.81±120.14ab	1110.83±156.39abcd	1781.4±225.86abc	2192.18±74.65b	279.3±5.44a	1276.8±43.49b	1791.68±167.26b	2255.69±143.62b
	B3N4	226.86±52.3bc	1007.03±164.06bcdef	1656.85±267.79cd	2061.14±90.35c	270.81±9.2b	1200.49±52.62c	1809.05±160.83b	2267.22±254.12b
	F-value								
	B	13.568**	23.478**	38.157**	82.906**	173.593**	86.334**	64.451**	27.359**
	N	2.588ns	4.811**	13.156**	449.455**	123.96**	449.441**	25.14**	21.849**
	B*N	0.269ns	0.658ns	0.671ns	2.533*	11.306**	2.533*	1.762ns	0.357ns
Total length of root cm/plant	B1N1	34.51±2.99c	114.56±6.85i	192.01±17.36e	210.02±17.64c	46.62±9.42d	146.82±34.66b	201.91±15.31d	277.72±10.81h
	B1N2	39.11±3.32b	156.86±5.25h	214.36±19.41d	238.49±19.69c	52.06±10.54cd	164.22±38.74b	225.98±16.79d	317.21±11.82f
	B1N3	41.53±5.55b	200.76±6.29d	241.55±26.29c	295.56±34.23b	66.21±18.7abc	198.38±29.14ab	262.09±32.08c	384.29±11.86bc
	B1N4	39.77±5.71b	193.39±7.53e	228.16±19.47cd	295.55±23.31b	55.07±20.62bcd	187.1±19.48ab	261.02±31.67c	367.32±12.99de
	B2N1	47.9±2.6a	165.19±7.33g	275.22±17.65b	366.48±62.87a	70.89±15.61ab	233.93±79.16a	284.49±27.65bc	303±13.44g
	B2N2	49.69±2.72a	205.86±7.95cd	284.88±18.14b	378.95±64.93a	73.55±16.13ab	242.66±81.72a	294.99±29.22b	377.62±14.58cd
	B2N3	49.63±4.43a	220.87±5.91a	306.55±13.35a	386.26±58.42a	73.18±17.91ab	253.27±102a	333.79±21.58a	405.16±10.85a
	B2N4	51.45±3.71a	213.23±5.39b	307.76±18.78a	384.07±48.83a	72.27±25.46ab	238.54±77.35a	321.83±29.23a	391.16±9.9b
	B3N1	39.73±2.01b	151.4±5.89h	195.45±8.74e	232.34±32.77c	60.86±14.86bcd	157.86±51.71b	212.78±19.67d	217.73±12.57i
	B3N2	48.24±2.47a	172.93±6.44f	237.14±11.13c	281.67±39.33b	72.15±18.11ab	191.07±62.11ab	259.51±23.1c	295.35±9.64g
	B3N3	51.21±4.47a	209.49±6.46bc	278.71±27.7b	367.98±66.68a	81.77±23.04a	238.81±82.39a	294.55±26.94b	375.88±11.54cd
	B3N4	47.48±5.63a	200.24±7.08d	276.22±16.87b	317.51±25.23b	69.66±12.22abc	184.9±28.37ab	293.75±29.87b	362.35±13.81e
	F-value								
	B	71.62**	253.052**	147.062**	65.824**	11.117**	11.208**	69.074**	197.992**
	N	14.795**	557.481**	49.501**	17.035**	3.007**	2.966**	35.962**	557.216**
	B*N	2.424*	20.401**	4.321**	3.116**	0.604ns	0.495ns	1.288ns	20.382**
Total surface area of root cm^2/plant	B1N1	25.88±11.45f	56.5±10.99d	84.07±9.14c	105.58±4.07g	33.28±2.12g	63.37±2.45g	101.46±16.19f	104.3±6.19f
	B1N2	29.56±12.91ef	67.92±15.94cd	93.96±10.28c	122.22±5.54f	37.78±2.29f	73.36±3.32f	113.43±18.17ef	128.58±7.1e
	B1N3	38.12±13.06bcdef	84.58±24.33abc	117.52±16.16b	149.69±5.18d	41.6±2.36e	89.84±3.11d	128.11±21.15de	158.88±18.36bcd
	B1N4	34.12±14.64cdef	74.05±20.45bcd	118.82±12.84b	142.64±6.29e	40.22±2.35e	85.61±3.77e	126.02±11.88de	149.29±29.88cd
	B2N1	45.5±12.06abcd	77.61±19.29abcd	125.36±21.2ab	123.21±8.49f	46.6±2.51cd	73.94±5.09f	143.02±21.98bcd	157.59±11.89bcd
	B2N2	47.14±12.43ab	93.16±28.54ab	129.85±21.8ab	153.07±4.25cd	48.32±2.56bc	91.86±2.55cd	148.32±22.51abc	163.45±12.55bc
	B2N3	51.53±13.45a	98.31±30.86a	138.39±13.88a	181.14±7.22a	49.83±2.39ab	108.71±4.34a	161.65±11.47a	186.81±36.75a

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	B2N4	50.78±10.5ab	100.56±22.18a	133.49±20.84ab	175.24±9.52a	50.66±2.26a	105.18±5.71a	159.17±19.4ab	187.17±11.63a
	B3N1	33.17±7.73def	70.93±13.74bcd	95.02±16.52c	125.72±2.82f	37.64±1.3f	75.46±1.69f	108.37±8.87f	128.44±10.04e
	B3N2	40.31±9.43abcde	77.6±22.32abcd	116.31±19.78b	157.08±6.26c	45.78±1.52d	94.28±3.76c	132.01±10.86bd	141.69±11.1de
	B3N3	46.74±10.8abc	90.52±18.91abc	129.28±20.14ab	179.87±6.9a	49.35±2.32ab	107.95±4.14a	146.7±18.6abc	169.17±17.25b
	B3N4	39.36±14.75abcde	86.23±18.23abc	118.35±15.36b	167.9±9.4b	47.02±1.49cd	100.77±5.64b	136.45±22.06bd	165.58±8.54bc
	F-value								
	B	17.404**	9.388**	25.061**	211.275**	222.829**	211.313**	38.004**	43.692**
	N	3.643*	5.994**	13.264**	324.535**	68.882**	324.825**	13.123**	33.489**
	B*N	0.257ns	0.223ns	1.701ns	3.918**	6.484**	3.922**	0.636ns	0.845ns
Total volume of root cm^3/plant	B1N1	0.53±0.07g	1.75±0.18d	2.44±0.47c	2.64±0.09g	0.66±0.04f	1.64±0.06g	2.5±0.19d	2.89±0.34h
	B1N2	0.6±0.08efg	1.95±0.21d	2.72±0.51bc	3.41±0.18e	0.74±0.04e	2.11±0.12e	2.78±0.21d	3.25±0.37gh
	B1N3	0.67±0.07cde	2.27±0.16bc	3.21±0.55ab	3.94±0.2c	0.77±0.04cde	2.44±0.13c	3.23±0.4c	3.89±0.3ef
	B1N4	0.63±0.07def	2.26±0.21c	3.08±0.53ab	3.37±0.14e	0.74±0.05de	2.1±0.09e	3.21±0.39c	3.91±0.31ef
	B2N1	0.78±0.07ab	2.38±0.1bc	3.32±0.3a	3.32±0.13e	0.79±0.06cd	2.06±0.08e	3.49±0.35bc	4.49±0.85cd
	B2N2	0.8±0.08a	2.46±0.1bc	3.43±0.3a	3.83±0.18c	0.81±0.04abc	2.37±0.11c	3.63±0.35b	4.65±0.88bcd
	B2N3	0.85±0.03a	2.7±0.15a	3.53±0.24a	4.97±0.22a	0.82±0.04abc	3.07±0.13a	4.1±0.26a	5.25±0.78a
	B2N4	0.82±0.14a	2.77±0.19a	3.47±0.51a	4.75±0.21b	0.86±0.03a	2.94±0.13b	3.95±0.36a	5.13±0.43ab
	B3N1	0.58±0.1fg	1.84±0.21d	2.49±0.59c	3±0.18f	0.66±0.08f	1.86±0.1f	2.64±0.23d	3.45±0.21fg
	B3N2	0.7±0.11bcd	2.24±0.25c	3.03±0.73ab	3.65±0.14d	0.8±0.1bcd	2.25±0.09d	3.19±0.29c	4.16±0.25de
	B3N3	0.78±0.11ab	2.48±0.19b	3.53±0.4a	4.76±0.18b	0.85±0.04ab	2.94±0.12b	3.63±0.32b	4.86±0.51abc
	B3N4	0.75±0.1abc	2.41±0.4bc	3±0.67ab	4.65±0.16b	0.8±0.06bcd	2.87±0.1b	3.61±0.37b	4.52±0.73cd
	F-value								
	B	47.853**	56.961**	12.476**	257.606**	27.272**	251.315**	67.042**	58.34**
	N	12.114**	34.367**	8.337**	448.807**	21.683**	436.712**	35.266*	20.959**
	B*N	1.19ns	1.245ns	1.323ns	20.908**	3.569**	20.081**	1.176ns	0.752ns
Tip number of root tips/plant	B1N1	106.03±16.53f	428.82±72.15d	600.34±37.73gh	697.25±77.1d	120.96±6.3e	417.79±21.54f	622.33±21.27g	659.51±62.33d
	B1N2	119.29±18.68def	479.63±81.69cd	589.53±38.51h	771.86±86.24cd	135.03±6.95d	508.67±21.99d	740.69±24.03e	831.01±194.92bc
	B1N3	132.81±13.45bcde	526.03±69.82c	637.87±34.34fg	877.97±133.48abc	144.16±10.11bc	640.49±19.6b	754.85±16.12e	834.18±109.64bc
	B1N4	127.61±15.83cde	526.03±77.64c	657.9±38.44ef	793.08±122.92bcd	138.78±5.05cd	617.67±21.95c	750.35±33.61e	817.95±139.19bc
	B2N1	144.38±21.75abc	606.68±76b	686.71±31.35e	910.71±127.33ab	137.34±9.4cd	479.97±17.9e	797±20.7cd	984.17±155.58a

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B2N2	149.41±22.5ab	629.43±79.31b	817.36±48.88b	943.48±131.9a	142.54±9.83bcd	600.22±27.9c	825.27±21.46b	931.68±162.68ab
B2N3	163.14±19.89a	702.67±38.25a	906.93±40.72a	963.34±139.38a	153.33±5a	685.63±23.25a	849.69±35.26a	978.71±145.72a
B2N4	147.75±21.36ab	689.6±42.83a	790.17±26.34bc	957.43±131.23a	155.44±4.13a	650.36±15.04b	867.04±36.9a	999.12±123.52a
B3N1	114.5±14.18ef	430.63±36.48d	634.39±52.52fg	697.39±91.99d	114.48±6.12e	421.55±29.98f	652.45±17.43f	716.64±73.48cd
B3N2	139.31±16.62	524.98±43.9c	767.63±37.98cd	833.8±112.86abc	139.59±7.61cd	526.16±21.69d	793.79±20.82d	844.31±82.24b
B3N3	145.93±20.26abc	619.02±57.79b	872.12±39.04a	933.61±158.78a	144.47±11.58bc	654.33±22.29b	821.41±16.32bc	889.04±50.16ab
B3N4	137.06±15.32bcd	625.02±55.56b	738.6±47.24d	800.98±170.6bcd	150.41±7.07ab	615.22±26.97c	812.42±27.6bcd	880.95±65.05ab
F-value								
B	23.996**	64.642**	192.987**	15.884**	25.831**	67.617**	195.455**	22.987**
N	9.039**	25.245**	76.67**	6.894**	55.203**	499.926**	135.107**	5.167**
B*N	0.752ns	1.737ns	14.427**	0.928ns	4.006**	3.272**	11.376**	1.734ns

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The amount of B and N had a significant effect on the RAR, FR, TLR, TSAR, TVR, TNR of tomato ($P \leq 0.05$). When the N was constant, the B increased from B1 to B3, resulting in the RAR, FR, TLR, TSAR, TVR, TNR of tomato in each treatment increased first and then decreased. The RAR, FR, TLR, TSAR, TVR, TNR of tomato in B2 were significantly higher than those in B1 by about 31.52% and 28.07% (mean growth period, the same below), 23.20% and 25.71%, 35.00% and 23.53%, 28.18% and 27.60%, 24.48% and 31.38%, 26.48% and 17.12%. It was higher than B3 about 12.36% and 13.85%, 14.51% and 16.31%, 18.86% and 17.85%, 9.52% and 11.60%, 10.67% and 12.36%, 13.25% and 11.55%. When the B was constant, the N increased from N1 to N4, resulting in the SDT of tomato in each treatment increased first and then decreased. The RAR, FR, TLR, TSAR, TVR, TNR of N3 was higher than that of N1 treatment by about 30.88% and 31.51%, 31.17% and 32.93%, 30.88% and 33.99%, 34.81% and 30.29%, 34.40% and 31.13%, 23.50% and 23.29%. It was higher than that of N2 treatment by about 14.95% and 15.92%, 13.03% and 16.47%, 14.81% and 15.63%, 15.73% and 14.75%, 16.91% and 16.64%, 10.58% and 7.57%. It was also higher than that of N4 treatment by about 4.53% and 3.48%, 4.66% and 1.56%, 3.73% and 5.79%, 5.17% and 3.36%, 5.38% and 3.47%, 7.01% and 1.27%.

Effects of different treatments on dry matter quality of greenhouse tomato

Effects of different treatments on dry matter quality of tomato in root, stem, leaf and fruit

From *Figure 3*, it can be seen that with the advancement of greenhouse tomato growth period, the dry matter mass of greenhouse tomato leaves (LDMM) increased first and then decreased, and the dry matter mass of stems (DDMM), roots (RDMM) and fruits (FDMM) increased. The B and N had a significant effect on the LDMM, DDMM, RDMM, FDMM of greenhouse tomato ($P \leq 0.05$).

When the N was constant, the B increased from B1 to B3, resulting in the LDMM, DDMM, RDMM, FDMM of tomato in each treatment increased first and then decreased. The LDMM, DDMM, RDMM, FDMM of greenhouse tomatoes in B2 was higher than that of B1 treatment by about 29.43% and 23.68% (mean growth period, the same below), 26.57% and 35.93%, 26.63% and 27.75%, 23.33% and 24.76%. The LDMM, DDMM, RDMM, FDMM of greenhouse tomatoes in B2 was also higher than that of B3 treatment by about 12.23% and 5.48%, 11.55% and 11.21%, 13.71% and 7.19%, 15.36% and 13.55%. When the B was constant, the N increased from N1 to N4, resulting in the LDMM, DDMM, RDMM, FDMM of tomato in each treatment increased first and then decreased. The LDMM, DDMM, RDMM, FDMM of N3 greenhouse tomato was higher than that of N1 by about 16.26% and 32.37%, 17.23% and 14.52%, 33.97% and 22.26%, 24.12% and 21.66%. It was also higher than that of N2 treatment by about 4.26% and 13.14%, 5.05% and 2.58%, 20.20% and 10.09%, 11.45% and 9.08%. It was also higher than that of N4 treatment by about 44.80% and 5.39%, 5.17% and 4.70%, 12.63% and 6.78%, 3.02% and 4.83%.

Comparative analysis of Logistic growth kinetics model parameters of total dry matter mass of tomato under different treatments

It can be seen from *Table 7* that the determination coefficient R2 of the Logistic model under different treatments is between 0.9980-0.9995, indicating that the Logistic model has high simulation accuracy. In the Logistic model, the parameter a can represent the maximum value of total dry matter mass of tomato. After calculation, the measured maximum value of total dry matter mass of tomato and the order of model parameter a value under different treatments showed that B2N3 was the highest. This shows that the order of the parameter a value of the Logistic model under different treatments is in good agreement with the order of the measured results, and the numerical values between the two are relatively close. In summary, the physical meaning of the Logistic model parameters of tomato growth is clear, and the response of the model parameter values and the measured values to each test treatment is in good agreement. Therefore, it is reasonable and feasible to use the Logistic model to quantitatively describe the dynamic change process of the total dry matter quality of greenhouse tomato by microbial fertilizers and chemical nitrogen fertilizers.

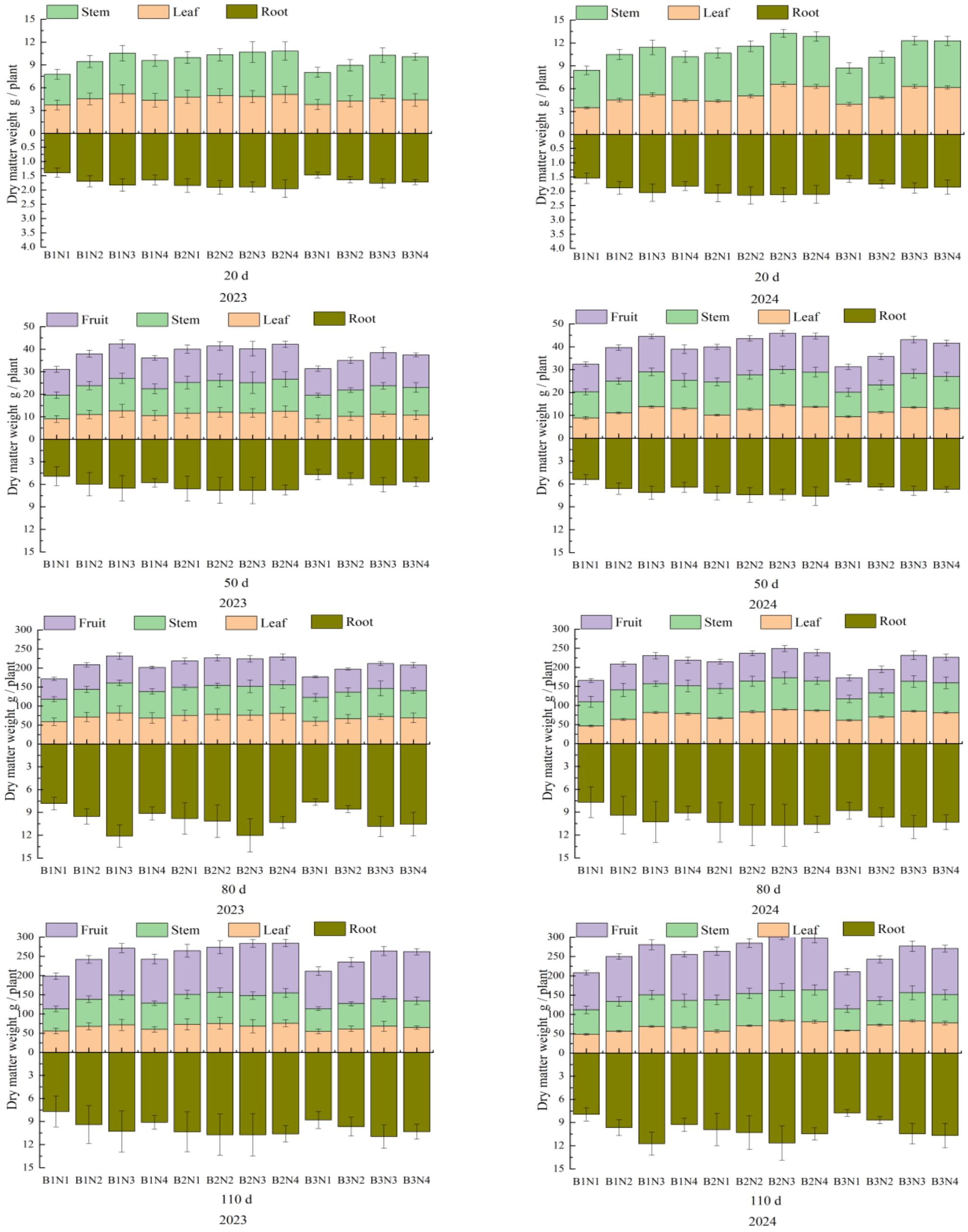

Figure 3. *Effects of microbial fertilizers and chemical nitrogen fertilizers on dry matter mass of greenhouse tomato*

Table 7. *Parameters of Logistic growth kinetic model of total dry matter mass with tomato (TDMQ)*

	Treatment	**a**	**b**	**c**	**R^2**	**MGR**	**LGR**	**TLG**
2023	B1N1	199.7123	6.9292	0.1064	0.9990	5.3123	4.6578	115.3040
	B1N2	221.9742	6.9518	0.1070	0.9995	5.9378	5.2062	128.1569
	B1N3	251.7960	6.5893	0.0992	0.9992	6.2445	5.4752	145.3745
	B1N4	249.5180	6.5766	0.0985	0.9990	6.1413	5.3846	144.0593
	B2N1	277.2955	6.7294	0.1032	0.9991	7.1542	6.2728	160.0966
	B2N2	287.1757	6.7418	0.1035	0.9991	7.4307	6.5152	165.8010
	B2N3	300.5951	6.5426	0.0979	0.9991	7.3571	6.4506	173.5487
	B2N4	299.8660	6.5265	0.0985	0.9992	7.3842	6.4744	173.1277
	B3N1	207.2373	7.1652	0.1126	0.9991	5.8337	5.1150	119.6485
	B3N2	252.8242	7.1238	0.1118	0.9991	7.0664	6.1958	145.9681
	B3N3	284.9593	7.0523	0.1101	0.9991	7.8435	6.8771	164.5213
	B3N4	255.1637	6.8164	0.1044	0.9991	6.6598	5.8392	147.3188
2024	B1N1	202.3667	6.4737	0.0978	0.9990	4.9458	4.3365	116.8365
	B1N2	227.1732	6.9372	0.1079	0.9989	6.1280	5.3730	131.1585
	B1N3	258.7615	6.9456	0.1085	0.9989	7.0189	6.1541	149.3960
	B1N4	251.2935	6.9181	0.1077	0.9990	6.7661	5.9325	145.0844
	B2N1	277.0712	6.5586	0.1002	0.9989	6.9406	6.0855	159.9671
	B2N2	298.1986	6.7384	0.1039	0.9989	7.7457	6.7914	172.1650
	B2N3	318.0439	6.6489	0.1017	0.9987	8.0863	7.0900	183.6227
	B2N4	312.7598	6.4161	0.0970	0.9988	7.5844	6.6500	180.5720
	B3N1	227.8858	6.7682	0.1044	0.9989	5.9478	5.2150	131.5699
	B3N2	279.1547	6.5477	0.0996	0.9989	6.9510	6.0946	161.1700
	B3N3	310.5428	6.3920	0.0963	0.9987	7.4763	6.5552	179.2920
	B3N4	281.2794	6.8316	0.1047	0.9986	7.3625	6.4554	162.3967

When the N was constant, the B increased from B1 to B3, resulting in the maximum linear growth rate (MGR), the average linear growth rate (LGR), the linear growth rate (TLG), the values of model parameter a (a) and the TDMQ greenhouse tomato in each treatment increased first and then decreased, the values of model parameter b (b) and model parameter c (c) of decrease first and then increase. When the B was constant, the N increased from N1 to N4, resulting in the MGR, LGR, TLG, a and TDMQ of tomato in each treatment increased first and then decreased, the b and c decreased.

Effects of different treatments on the quality of greenhouse tomatoes

Fruit shape

It can be seen from *Table 8* that the effect of the B on the WSF, WDSF, TDSF of tomato fruit reached a significant level ($P \leq 0.05$), and the relative contributions were 84.40% and 8.90%, 16.70% and 15.20%, 22.80% and 12.10%, respectively. When the N was constant, the B increased from B1 to B3, resulting in the WSF, WDSF, TDSF of tomato fruit in each treatment increased first and then decreased. The WSF, WDSF, TDSF of tomato treated with B2 was also higher than B1 by about 26.38% and 18.84%, 17.52% and 9.60%, 18.47% and 10.04% higher than those of B1. It was also higher than B3 by about 5.06% and 13.24%, 11.46% and 3.60%, 15.31% and 3.30%.

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Table 8. *Effects of microbial fertilizers and chemical nitrogen fertilizers on quality of greenhouse tomato*

	Treatment	**Fruit shape**			**Fruit flavor**			**Fruit nutrient**		
		WSF g	**WDSF mm**	**TDSF mm**	**SOC %**	**TSUC %**	**SA**	**TSPC mg/g**	**VCC mg/g**	**LC %**
2023	B1N1	74.3±2.43e	41.81±7.81d	43.81±8.26f	8.23±0.36	5.31±1.09	4.78±1.09	4.35±0.43d	11.85±0.93d	32.64±4.53d
	B1N2	96.23±5.31e	50.93±9.71bc	53.31±9.99de	10.05±0.4	6.57±1.34	6.73±1.32	4.85±0.48c	13.22±1.03c	37.38±4.69d
	B1N3	111.2±5.63c	54.91±12.44ab	68.68±13.18abc	10.09±0.12	6.85±1.13	8.23±1.31	6.3±0.18c	14.09±0.83c	40.14±5.22c
	B1N4	95.29±4.04e	51.38±7.5bc	60.22±10.39cd	10.45±0.5	6.39±1.44	7.74±0.93	5.03±0.57c	13.1±1.03c	44.81±5.09c
	B2N1	93.61±3.77e	53.89±6.52abc	60.42±4.86cd	14.83±0.46	9.63±1.68	10.09±2.6	7.4±0.86b	21.84±1.41ab	63.23±4.85a
	B2N2	107.91±4.97c	55.86±6.83ab	62.62±5.02bcd	15.38±0.49	9.99±1.73	11.57±2.71	7.67±0.9b	22.53±1.46ab	65.58±5.07a
	B2N3	140.5±6.19a	63.1±6.54a	74.25±11.13a	18±2.04	12.56±2.15	13.65±2.26	9.98±0.56a	23.95±2.77a	67.42±9.14a
	B2N4	134.47±5.98b	61.04±4.4a	70.46±3.32ab	14.84±1.28	9.37±1.84	8.78±1.75	7.37±0.47b	21.26±2.97b	61.21±12.26a
	B3N1	84.6±4.85e	45.07±10.71cd	49.49±9.62f	14.36±0.43	8.41±1.14	8.74±2.21	6.46±0.42c	18.26±1.4b	61.66±5.78a
	B3N2	102.97±4.05d	50.36±12.04bc	55.35±10.78de	16.02±0.47	10.23±1.34	10.94±2.44	7.85±0.5b	22.3±1.77ab	54.46±5.65b
	B3N3	134.52±5.21b	57.47±6.28ab	65.81±10.01abc	15.09±0.38	10.65±1.84	10.8±1.25	9.59±1.01a	21.6±1.73b	66.81±6.57a
	B3N4	131.45±4.52b	56.95±8.84ab	61.54±5.16bcd	15.04±1.18	11.69±1.2	10.52±2.15	8.29±0.74b	20.49±4.82b	65.4±6.54a
	F-value									
	B	59.093(84.40)**	9.607(16.70)**	14.144(22.80)**	547.832(91.90)**	83.664(63.50)**	47.066(49.50)*	256.824(84.30)**	191.327(79.90)*	163.831(77.30)**
	N	45.829(93.40)**	9.210(22.80)**	20.273(40.20)**	24.083(42.90)**	9.795(23.40)**	11.669(26.70)**	78.178(71.00)**	7.580(19.20)*	5.484(14.60)*
	B*N	20.946(56.70)**	0.502(2.40)ns	1.259(4.00)ns	11.133(41.00)**	3.749(19.00)*	3.506(18.00)**	4.609(22.40)*	1.375(7.90)ns	3.760(19.00)**
2024	B1N1	77.86±13.22d	42.46±5.56d	47.86±4.71d	9.87±1.63e	5.54±0.38e	7.43±1.02d	4.94±0.48d	11.88±2.42d	40.75±6.38d
	B1N2	95.1±15.92bcd	51.58±6.64c	58.4±5.57bc	11.04±1.82e	6.91±0.28e	9.04±1.24d	6.02±0.58d	14.97±2.98c	50.26±7.68c
	B1N3	128.73±43.44a	61.64±6.5bc	67.44±7.01a	10.52±0.59e	8.59±0.29cd	9.64±1.58cd	6.23±0.71cd	14.89±1.96c	49.22±7.54c
	B1N4	126.25±30.99a	61.59±4.76bc	66.94±4.84a	9.94±1.07e	8.07±0.35de	9.96±1.71c	5.95±0.18d	15.93±1.87c	50.82±4.44c
	B2N1	122.16±24.56abc	57.73±5.21bc	63.78±7.56abc	14.79±1.53cd	8.67±0.32cd	12.99±2.17b	8.19±0.62b	22.09±2.89ab	71.67±10.87ab
	B2N2	126.55±25.41a	59.75±5.34bc	66.04±7.85a	15.31±1.57c	10.81±0.5bc	13.41±2.23b	8.48±0.65b	22.91±3a	74.05±11.18a
	B2N3	133.28±25.63a	62.64±3.53a	68.79±4.46a	18.22±1.57a	12.34±0.43a	15.51±2.23a	9.53±0.94a	24.44±0.76a	74.8±4.68a
	B2N4	126.55±24.92a	58±3.03bc	66.19±6.62a	14.76±2.69cd	11.71±0.27a	12.85±1.42b	8.4±0.57b	21.98±1.93ab	68.41±7.68
	B3N1	92.7±26.48cd	50.71±6.91c	58.01±9.49c	13.27±1.07d	8.08±0.4de	10.22±1.58c	7.47±0.76c	19.88±2.14b	65.19±5.55b

Treatment	Fruit shape			Fruit flavor			Fruit nutrient		
	WSF g	**WDSF mm**	**TDSF mm**	**SOC %**	**TSUC %**	**SA**	**TSPC mg/g**	**VCC mg/g**	**LC %**
B3N2	103.51±36.45bcd	56.66±7.66b	64.84±10.65abc	16.23±1.29bc	9.71±0.39bc	11.43±1.77bc	8.36±0.86b	22.22±2.39ab	72.94±6.27ab
B3N3	129.7±45.44a	61.37±4.27bc	65.58±8.12ab	17.26±1.81ab	11.53±0.34ab	12.13±1.19b	9.38±0.33ab	22.04±2.35ab	70.3±8.6ab
B3N4	123.19±14.44ab	61.11±2bc	67.91±6.16a	15.73±0.92bc	11.12±0.41b	11.79±2.96b	8.57±0.87b	23.19±3.17a	71.39±8.5ab
F-value									
B	4.666(8.90)*	8.610(15.20)**	6.595(12.10)**	142.785(74.80)**	950.640(95.20)**	58.349(54.90)**	207.618(81.20)**	131.818(73.30)**	110.205(69.70)**
N	7.435(18.90)**	25.037(43.90)**	13.158(29.10)**	14.545(31.20)**	446.375(93.30)**	6.628(17.20)**	23.390(42.20)**	6.515(16.90)**	3.766(10.50)*
B*N	1.233(7.20)ns	5.423(25.30)*	2.784(14.80)*	3.736(18.90)*	2.473(13.40)*	1.335(7.70)ns	3.869(9.30)*	4.105(10.40)*	1.270(7.40)*

The effects of N on WSF, WDSF, TDSF of tomato were significant (P≤0.05), and the highest relative contributions were 93.40% and 18.90%, 22.80% and 43.90%, 40.20% and 29.10%, respectively. When the B was constant, the N increased from N1 to N4, resulting in the LDMM, DDMM, RDMM, FDMM WSF, WDSF, TDSF of tomato in each treatment increased first and then decreased.

Fruit flavor

It can be seen from *Table 7* that the effect of B on TSOC, TSUC, SA of tomato fruit reached a significant level (P≤0.05), and the relative contributions were 91.90% and 74.80%, 63.50% and 95.20%, 49.50% and 54.90%, respectively.

When the N was constant, the B increased from B1 to B3, resulting in the TSOC, TSUC, SA of tomato fruit in each treatment increased first and then decreased. The TSOC, TSUC, SA of tomato fruit treated with B2 were higher than those of B1 by about 62.36% and 52.50%, 65.40% and 49.55%, 60.47% and 51.85%. It was also higher than B3 by about 4.19% and 0.96%, 1.39% and 7.64%, 7.51% and 20.20%. The effects of N on TSOC, TSUC, SA of tomato were significant (P≤0.05), and the highest relative contributions were 42.90% and 31.20%, 24.30% and 93.30%, 26.70% and 17.20%, respectively. When the B was constant, the N increased from N1 to N4, resulting in the TSOC, TSUC, SA of tomato in each treatment increased first and then decreased. Among them, the TSOC, TSUC, SA of tomato treated with N3 were higher than those of N1 by about 15.99% and 21.28%, 28.76% and 45.63%, 41.14% and 21.65%, respectively. It was also higher than N2 by about 3.83% and 8.03%, 11.47% and 18.37%, 12.71% and 10.04%. It was also higher than N4 by about 6.01% and 13.75%, 9.30% and 5.09%, 19.27% and 7.70%.

Fruit nutrient

It can be seen from *Table 8* that the effect of B on TSPC, VCC, LC of tomato fruit reached a significant level (P≤0.05), and the relative contribution rates were 84.30% and 81.20%, 79.90% and 73.30%, 77.30% and 69.70%, respectively.

When the N was constant, the B increased from B1 to B3, resulting in the TSOC, TSUC, SA of tomato fruit in each treatment increased first and then decreased. Among them, the TSPC, VCC, LC of tomato fruit treated with B2 were higher than those of B1 by about 57.93% and 49.56%, 71.39% and 58.55%, 66.12% and 51.24%. It was also higher than B3 by about 0.74% and 2.45%, 8.40% and 4.68%, 3.67% and 3.26%. The effects of N on TSPC, VCC, LC of tomato were significant (P≤0.05), and the highest relative contributions were 71.00% and 42.20%, 19.20% and 16.90%, 14.60% and 10.50%, respectively. When the B was constant, the N increased from N1 to N4, resulting in the TSPC, VCC, LC of tomato in each treatment increased first and then decreased. Among them, the TSPC, VCC, LC of tomato treated with N3 were higher than those of N1 by about 42.06% and 22.11%, 14.80% and 13.97%, 10.69% and 9.41%, respectively. It was higher than N2 by about 27.00% and 10.01%, 2.74% and 2.12%, 10.77% and-1.48%, and also higher than N4 by about 25.04% and 9.68%, 8.73% and 0.44%, 1.72% and 1.94%.

Comprehensive evaluation of tomato quality based on PCA

When the principal component comprehensive evaluation of tomato fruit quality was carried out, the principal component (*Table 9*) was extracted according to the principle

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that the characteristic value was greater than 1. It can be seen from *Table 9* that the cumulative contribution rate of PC1 and PC2 was more than 90%. The variance contribution rate of the first principal component PC1 is more than 55%, which mainly reflects the morphological index of tomato fruit appearance and is directly related to the commodity value of tomato. Therefore, PC1 can be called commodity factor. The variance contribution rate of the second principal component PC2 was more than 35%, which mainly reflected the flavor and nutritional indexes of tomato fruit. Soluble solids were related to tomato taste, and soluble protein was rich in nutritional value. Therefore, PC2 could be called taste nutritional factor. The comprehensive quality score (*Table 10*) showed that the quality of tomato treated with B2N3 was the best.

Table 9. *Factor loadings and variance contribution rates of the principal component*

Variables	2023		2024	
	PC1	PC2	PC1	PC2
X1	0.411	0.866	0.297	0.934
X2	0.380	0.910	0.294	0.947
X3	0.257	0.940	0.350	0.916
X4	0.946	0.284	0.960	0.209
X5	0.891	0.408	0.756	0.586
X6	0.852	0.434	0.835	0.474
X7	0.823	0.509	0.928	0.352
X8	0.932	0.295	0.933	0.336
X9	0.907	0.285	0.943	0.285
Characteristic values	7.282	1.204	7.202	1.395
Variance contribution rates%	57.349	36.943	56.071	39.445
Cumulative contribution rates%	57.349	94.292	56.071	95.516

Table 10. *Comprehensive score of principal component of tomato quality*

Treatment	2023	2024
B1N1	0.00	0.00
B1N2	0.55	0.71
B1N3	0.96	1.14
B1N4	0.72	1.12
B2N1	1.68	1.89
B2N2	1.92	2.16
B2N3	2.67	2.65
B2N4	1.88	2.06
B3N1	1.19	1.26
B3N2	1.70	1.89
B3N3	2.14	2.25
B3N4	2.01	2.14

Effects of different treatments on tomato yield, bacterial nitrogen partial productivity and net income in greenhouse

The total cost of greenhouse tomato irrigation facilities, site leasing, seeds, seedlings, pesticides, labor and other management was about 73,100 yuan/ha. The unit price of *Bacillus subtilis* was 23.00 yuan/kg, *Trichoderma harzianum* was 32.00 yuan/kg, and nitrogen fertilizer was 61.00 yuan/kg. The price of tomatoes is calculated according to the average annual purchase price of local tomatoes of 5.00 yuan/kg. The net income of greenhouse tomato in this study is shown in *Table 11*.

Table 11. *Effects of microbial fertilizers and chemical nitrogen fertilizers on yield (YD), bacterial nitrogen partial factor productivity (BNPP) and net income (NI) of greenhouse tomato*

Treatment	**2023**			**2024**		
	YD kg/hm^2	**BNPP kg/kg**	**NI yuan/hm^2**	**YD kg/hm^2**	**BNPP kg/kg**	**NI yuan/hm^2**
B1N1	79584.34± 4313.25f	1094.06± 61.62a	320551.71± 21566.26f	87136.13± 4274.86f	1187.66± 61.07a	358310.64± 21374.31e
B1N2	93738.45± 5165.88e	648.13± 36.9b	387052.25± 25829.39e	99746.23± 4110.71de	683.9± 29.36b	417091.14± 20553.54cd
B1N3	93333.47± 5493.26e	453.97± 26.16c	380757.36± 27466.29e	112044.08± 4224.72bc	514.5± 20.12d	474310.39± 21123.62b
B1N4	83828.7± 3938.85ef	313.67± 14.07g	328963.49± 19694.25f	107628.59± 5112.53d	370.1± 18.26e	447962.94± 25562.64c
B2N1	96176.91± 3676.29de	644.12± 26.26b	403514.55± 18381.45e	95988.4± 3392.4ef	649.92± 24.23c	400692.02± 16962e
B2N2	105113.79± 4841.44c	462.45± 23.05c	443928.96± 24207.18d	113786.91± 5290.09b	503.75± 25.19d	485414.53± 26450.44ab
B2N3	119662.49± 5868.62a	436.29± 20.96cd	512402.47± 29343.09a	117976.45± 4407.1a	430.27± 15.74d	502092.27± 22035.51a
B2N4	117555.81± 2854.34ab	343.02± 8.16ef	497599.06± 14271.68ab	114291.71± 2851.32ab	333.69± 8.15f	479398.53± 14256.61b
B3N1	87388.93± 4731.46ef	416.14± 22.53d	359574.64± 23657.29f	89888.23± 4083.85f	428.04± 19.45e	368311.13± 20419.26e
B3N2	100313.31± 3953.48d	358.26± 14.12e	419926.54± 19767.39e	102117.01± 4168.37de	364.7± 14.89f	425185.07± 20841.86c
B3N3	116064.77± 5077.92ab	331.61± 14.51fg	494413.86± 25389.6ab	109418.89± 3716.97cd	312.63± 10.62f	457424.44± 18584.87b
B3N4	114607.12± 2742.95b	272.87± 6.53g	482855.61± 13714.77c	108094.11± 4160.7cd	257.37± 9.91f	446530.53± 20803.49c
F-value						
B	237.469 (83.20)**	992.769 (95.40)**	237.469 (83.20)**	49.518 (50.80)**	1730.911 (97.30)**	49.238 (50.60)**
N	121.330 (79.10)**	1126.313 (97.20)**	99.006 (75.60)**	49.518 (82.10)**	1465.987 (97.90)**	120.289 (79.00)**
B*N	19.321 (53.30)**	272.036 (94.40)**	18.231 (53.30)**	2.240 (12.30)*	322.400 (95.30)**	2.240 (12.30)*

From *Table 6*, it can be seen that the effect of the B on tomato YD, BNPP and NI reached a significant level ($P \leq 0.05$), and the relative contributions were 83.20% and 50.80%, 95.4% and 97.30%, 83.20% and 50.60%, respectively. The effects of N on tomato YD, BNPP and NI reached a significant level($P \leq 0.05$), and the highest relative contributions were 79.10% and 82.10%, 97.20% and 97.70%, 75.60% and 79.00%, respectively. The tomato YD of B2N3 treatment was higher than that of B1N1, B1N2, B1N3, B1N4, B2N1, B2N2, B2N4, B3N1, B3N2, B3N3, B3N4 by about 50.36% and 35.39%, 27.66% and 18.28%, 28.21% and 5.29%, 42.75% and 9.61%, 24.42% and 22.91%, 13.84% and 3.68%, 1.79% and 3.22%, 36.93% and 31.25%, 19.29% and 15.53%, 3.10% and 7.82%, 4.41% and 9.14%. Although the BNPP in tomato treated with B2N3

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was lower than that of B1N1, B1N2, B1N3, B2N1 and B2N2 by about 60.12% and 63.77%, 32.68% and 37.09%, 3.89% and 16.37%, 32.27% and 33.80%, 5.66% and 14.59%, respectively. However, the BNPP of B2N3 treatment was higher than that of B1N4, B2N4, B3N1, B3N2, B3N3 and B3N4 by about 39.09% and 16.26%, 27.19% and 28.94%, 4.48 and 0.52%, 21.78% and 17.98%, 31.57% and 37.63%, 59.89% and 67.82%. The tomato NI of B2N3 treatment was higher than that of B1N1, B1N2, B1N3, B1N4, B2N1, B2N2, B2N4, B3N1, B3N2, B3N3, B3N4 by about 59.85% and 40.13%, 32.39% and 20.38%, 34.57% and 5.68%, 55.76% and 12.08%, 26.98% and 25.31%, 15.42% and 3.44%, 2.97% and 4.73%, 42.50% and 36.32%, 22.02% and 18.09%, 3.64% and 9.77%, 6.12% and 12.44%.

When the N was constant, the B increased from B1 to B3, resulting in the YD and NI of tomato in each treatment increased first and then decreased. The YD and NI of tomato in B2 treatment were higher than those in B1 by about 25.11% and 8.73%, 31.05% and 10.01%, and also higher than those in B3 by about 4.81% and 7.94%, 5.73% and 10.02%. The BNPP showed a decreasing trend. The BNPP in B2 treatment was lower than that in B1 by about 24.86% and 30.42%, but significantly higher than that in B3 by about 36.77% and 40.72%. When the B was constant, the N increased from N1 to N4, resulting in the YD and NI of tomato in each treatment increased first and then decreased. The YD and NI of N3 treatment were higher than those of N1 by about 25.05% and 24.33%, 28.05% and 27.19%, higher than those of N2 by about 9.99% and 7.54%, 10.93% and 7.99%, and higher than those of N4 by about 4.14% and 2.86%, 5.97% and 4.36%. The BNPP showed a decreasing trend. The BNPP in B2 treatment was lower than that in N1 by about 43.28% and 44.50%, lower than that in N2 by about 16.81% and 19.00%, but significantly higher than that in N4 by about 31.45% and 30.82%.

TOPSIS comprehensive benefit optimal evaluation

Five indicators of tomato total dry matter mass (TDMQ), fruit quality comprehensive score, YD, BNPP and NI were selected as evaluation variables. The TOPSIS method is used to construct the comprehensive benefit evaluation model (*Table 12*). The results of TOPSIS comprehensive benefit evaluation model showed that (*Table 12*) the comprehensive benefit of B2N3 was the best (0.606 and 0.604), which further indicated that the combination of B and N reduction B2N3 was not only beneficial to the improvement of fruit quality, BNPP and YD of greenhouse tomato, but also significantly increased the NI of tomato.

Table 12. *The ranking of treatments calculated using TOPSIS*

Treatment	**2023**				**2024**			
	D_+	**D_-**	**C_i**	**Ranking**	**D_+**	**D_-**	**C_i**	**Ranking**
B1N1	0.772	0.636	0.452	7	0.776	0.631	0.448	7
B1N2	0.654	0.367	0.359	9	0.627	0.390	0.384	11
B1N3	0.688	0.335	0.327	10	0.554	0.539	0.493	5
B1N4	0.857	0.228	0.210	12	0.667	0.431	0.392	10
B2N1	0.497	0.537	0.520	4	0.561	0.487	0.465	6
B2N2	0.539	0.582	0.519	5	0.479	0.680	0.587	2
B2N3	0.509	0.782	0.606	1	0.514	0.785	0.604	1
B2N4	0.592	0.702	0.542	2	0.591	0.672	0.532	3
B3N1	0.804	0.227	0.220	11	0.806	0.241	0.231	12
B3N2	0.668	0.432	0.393	8	0.65	0.466	0.417	9
B3N3	0.599	0.676	0.530	3	0.618	0.624	0.502	4
B3N4	0.671	0.589	0.468	6	0.675	0.545	0.447	8

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Discussion

Effect of microbial fertilizers and chemical nitrogen fertilizers on growth of greenhouse tomato

Microorganisms (*Bacillus subtilis*, *Trichoderma harzianum*) can colonize the rhizosphere of plants and form biofilms. Biofilms not only protect roots from pathogens, but also produce a variety of plant hormones and growth regulators such as indole acetic acid and gibberellin through their life activities. These hormone regulators can enhance the absorption capacity of plants to major nutrients such as nitrogen, phosphorus, and potassium, and promote cell division and elongation (Shang et al., 2023; Fan et al., 2025). In addition, microorganisms can effectively promote the transformation and release of soil nutrients through nitrogen fixation, dissolution of insoluble phosphorus and potassium minerals in the soil, and production of metabolites such as organic acids, providing a richer source of nutrients for plants, thereby improving the growth efficiency and development quality of plants as a whole (Blake et al., 2021; Psdo et al., 2022). In this study, the significant effect of the amount of bacteria on the growth and development of greenhouse tomatoes revealed the key role of soil microorganisms in crop growth. From the leaf P*n*, LAI, PHT, SDT to root morphology and other indicators, the growth of tomato treated with appropriate amount of bacteria (B2) was significantly better than that without bacteria (B1) or excessive bacteria (B3). It may be due to the optimization of soil microbial community structure by B2, which significantly improved soil nutrient transformation and release, aggregate formation and aeration, increased soil ion exchange frequency, increased the contact rate of crops and soil organic matter, and promoted the absorption of nutrients and water by roots. These beneficial microorganisms produce metabolites through their life activities, effectively absorb and transform the original harmful substances in the soil, form a new microbial system, improve the soil micro-environment, and reduce soil pathogens. *Bacillus subtilis* secretes IAA to amplify mesophyll cells, and *Trichoderma harzianum* activates phosphorus to enhance ATP synthesis, which together create more favorable conditions for the growth of tomatoes. Excessive application of bacteria can lead to imbalance of soil microbial community, accumulation of competitive nutrients or toxic metabolites among microorganisms, resulting in imbalance of root-shoot synergy and inhibition of growth index optimization (Liu et al., 2024a; Wei et al., 2024). For example, the soil environment of B2 treatment directly promoted the enhancement of plant photosynthesis, leaf growth and root development, and promoted the dry matter quality of B2 tomato leaves, stems, roots and fruits to be higher than that of B1 by about 29.43% and 23.68% (mean growth period, the same below), 26.57% and 35.93%, 26.63% and 27.75%, 23.33% and 24.76%; it was higher than B3 about 12.23% and 5.48%, 11.55% and 11.21%, 13.71% and 7.19%, 15.36% and 13.55%. This study is consistent with the increase of *Bacillus subtilis* in soil is beneficial to tomato leaf photosynthesis, growth and root morphological development (Shao and Tan, 2012; Almoneafy et al., 2014; Psdo et al., 2023; Liu et al., 2024b). However, other researchers (Wang et al., 2025) found that there was no significant difference in tomato PHT and SDT with the increase of the amount of bacteria applied, which was inconsistent with the conclusion of this study. It may be due to the difference in the types of microbial agents. Wang used Trichoderma and *Bacillus atrophaeus*. In this study, *Bacillus subtilis* and *Trichoderma harzianum* were used.

As the core nutrient element of plant growth and development, nitrogen drives life activities through multi-dimensional physiological mechanisms: it is the key component of chloroplast chlorophyll (Chl a/b), photosystem II core protein D1 and Rubisco enzyme, which directly determines the efficiency of light energy capture and carbon assimilation. At the same time, as the basis for the synthesis of amino acids, nucleic acids, hormones (such as cytokinin CTK and auxin IAA) and coenzymes, it is involved in protein synthesis, cell division and elongation, root configuration optimization (such as root length density and specific root surface area) and other morphogenesis processes, which are specifically manifested in the increase of plant height, leaf area and stem diameter of crops, and comprehensively improve the overall growth rate and biomass accumulation of crops (Zhang et al., 2023b, 2024).This study also found that with the increase of N, the P*n*, LAI, SDT, PHT, root morphological development and dry matter mass of greenhouse tomato increased first and then decreased. This may be due to low to medium nitrogen levels (N1 to N3), nitrogen synergistically drives increased photosynthetic carbon assimilation efficiency, leaf area expansion and root meristem activation by promoting increased chlorophyll a/b ratio in chloroplasts, enhanced Rubisco enzyme activity, and cytokinin/auxin synthesis (Root length/surface area optimization), while carbon and nitrogen metabolism are coordinated (Interaction of carbohydrates and amino acids) Promote stem diameter and dry matter accumulation; However, when the amount of nitrogen application exceeds the threshold (N4), excess nitrogen breaks the carbon-nitrogen balance, preferentially synthesizes nitrogen-containing compounds, leads to a shortage of carbon skeleton (such as carbohydrates), weakens cell wall (cellulose/lignin) synthesis and reduces stem mechanical strength. At the same time, the accumulation of high concentrations of NO_3^- in the rhizosphere causes osmotic stress (inhibition of water absorption) and membrane lipid peroxidation (increased MDA). Antagonistic effect of superimposed nitrogen excess on K^+, Ca^{2+}, Mg^{2+} absorption (affects photosynthetic electron transport and cell wall stability), while leaf nitrogen distribution is biased towards the photosynthetic apparatus, resulting in an imbalance between light energy capture and carbon assimilation. Excess light energy induces a burst of reactive oxygen species (ROS) and damages the PSII reaction center (Fv/Fm decrease), coupled with ABA signal-mediated decrease in stomatal conductance and non-stomatal restriction (such as PEP carboxylase inhibition), as well as the excessive distribution of assimilates to stems and leaves caused by activation of the TOR kinase pathway (excessive length accompanied by excessive LAI shading), resulting in a downward trend in photosynthetic rate, leaf area index, plant height, stem thickness, root morphology development and dry matter quality (Lei et al., 2024a; Li et al., 2025). With the increase of nitrogen application rate, the stem diameter of tomato increased first and then decreased (Wang et al., 2020); the dry matter mass of tomato increased first and then decreased with the increase of nitrogen application rate (Yuan et al., 2022; Lei et al., 2024a), which was consistent with the conclusion of this study. It is also consistent with the conclusion of the effect of nitrogen application rate on tomato root morphological development (Wang et al., 2019).

Effects of microbial fertilizers and chemical nitrogen fertilizers on fruit quality of greenhouse tomato

The synergistic interaction between *Bacillus subtilis* and *Trichoderma harzianum* enhances tomato fruit quality through multi-dimensional mechanisms. Bacillus subtilis improves postharvest preservation by secreting indole-3-acetic acid (IAA) and ACC deaminase, which delay ethylene-mediated fruit softening, while its lipopeptide antimicrobial metabolites effectively suppress pathogen invasion (e.g., Botrytis cinerea) and reduce postharvest decay. Concurrently, *Trichoderma harzianum* expands root absorption capacity through hyphal network extension and secretes organic acids/phosphatases to mobilize mineral elements (e.g., calcium and magnesium), thereby promoting sugar metabolism and carotenoid/lycopene biosynthesis for optimized fruit coloration (Fall et al., 2004; Chen et al., 2024; Pomerleau et al., 2024). The microbial consortium synergistically enhances fruit quality through coordinated organic matter decomposition and nutrient mineralization, enhanced rhizosphere nitrogen-phosphorus acquisition efficiency coupled with directional translocation of photosynthetic assimilates, and systemic resistance induction that activates antioxidant enzymes including superoxide dismutase (SOD) and peroxidase (POD). These mechanisms collectively increase soluble solids (sugar accumulation), vitamin C content and uniformity, while reducing lipid peroxidation damage. Notably, they regulate sugar-acid metabolism balance by elevating fructose/glucose/sucrose ratios and optimizing sugar-acid profiles (Ahemad and Khan, 2011; Vuyyuru et al., 2018; Imran et al., 2024).This study observed a biphasic dose-response relationship between microbial inoculant application levels and greenhouse tomato fruit quality, where the fruit shape, fruit flavor, fruit nutrient exhibited an initial enhancement followed by progressive decline with excessive dosing. This phenomenon may result from the dual-phase regulatory mechanisms of *Bacillus subtilis* and *Trichoderma harzianum*. At moderate doses (B2), these microorganisms secrete bioactive compounds such as phosphorus-solubilizing enzymes and potassium-mobilizing enzymes, which facilitate the conversion of recalcitrant soil nutrients (e.g., insoluble phosphates, fixed potassium) into bioavailable forms. This nutrient solubilization drives cellular expansion through enhanced vacuolar hydration and cell wall loosening (increasing fruit weight and dimensions) while modulating sugar-acid metabolism via the upregulation of key enzymes (e.g., sucrose phosphate synthase and citrate synthase), thereby promoting soluble sugar accumulation and optimizing sugar-acid balance. Concurrently, microbial-derived signaling molecules activate antioxidant systems, stimulating the biosynthesis of vitamin C through the L-galactose pathway and enhancing lycopene production via carotenoid metabolic flux. However, excessive application (B3 treatment) disrupts rhizosphere equilibrium through three interconnected mechanisms: microbial overproliferation-induced soil acidification, competitive nutrient depletion, and accumulation of phytotoxic secondary metabolites. These perturbations impair photosynthate allocation by downregulating sucrose transporter genes), reduce sink strength via inhibition of hexose transporters, and disrupt sugar-acid coordination through suppressed malate dehydrogenase activity. The resultant metabolic dysregulation manifests as quality deterioration characterized by reduced soluble solids, imbalanced sugar-acid profiles, and oxidative damage from lipid peroxidation (Zhou et al., 2021; Demir et al., 2023). The conclusion is consistent with Mena-Violante's (Mena-Violante and Olalde-Portugal, 2007) study on the improvement of tomato fruit quality by increasing *Bacillus subtilis* in soil, which highlights *Bacillus subtilis*-mediated fruit quality enhancement through rhizosphere nutrient mobilization. Importantly, this study expands the paradigm by identifying a critical microbial density threshold (B2 as optimal) that balances beneficial bioactivity with ecological stability, underscoring the necessity of precision dosage control in microbial-assisted horticulture to avoid the transition from symbiotic nutrient cycling to dysbiotic stress.

Previous studies have found that auxin and cytokinin (CTK) synergistically promote root architectural plasticity under nitrogen availability, driving primary root elongation and lateral root initiation through auxin efflux carrier-mediated polar auxination and CTK-modulated cell division patterns. Conversely, abscisolic acid (ABA) antagonizes these morphogenetic responses via ABA-responsive transcription factors (e.g., ABI4) that suppress root meristem activity. Optimal nitrogen supplementation upregulates nitrate transporter genes (NRT1.1, NRT2.1), enhances nitrogen use efficiency (NUE) through ammonium assimilation pathway activation, and sustains systemic carbon-nitrogen homeostasis by coordinating glutamine synthetase (GS)/glutamate synthase (GOGAT) cycling. This nitrogen-mediated reprogramming enhances root system functionality by expanding the root nutrient acquisition surface area through increased root hair density and branching topology, thereby optimizing photosynthetic partitioning and ultimately enhancing fruit quality parameters including soluble solids accumulation and nutritional compound biosynthesis (Li et al., 2024a; Fidler et al., 2025).This study found that with the increase of N, the fruit shape, fruit flavor, fruit nutrient index parameters of greenhouse tomato showed a trend of increasing first and then decreasing. It may be due to the fact that the B2 supplementation enhances fruit quality by stimulating plant growth through auxin-cytokinin crosstalk, upregulating photosynthetic efficiency via RuBisCO activation, and promoting phloem-mediated nutrient translocation to fruits through sucrose transporter (SWEET11/12)-dependent pathways, which collectively drive cellular expansion and carbohydrate accumulation. However, excessive nitrogen application induces a metabolic cascade of detrimental effects: soil acidification and ammonium toxicity disrupt rhizosphere microbiota equilibrium, while photosynthetic feedback inhibition via reactive oxygen species (ROS) overproduction impairs carbon fixation. Concurrently, nitrogen hyperaccumulation disrupts carbon-nitrogen homeostasis, suppressing citrate synthase activity in the TCA cycle and diverting resources toward glutamine synthesis at the expense of flavor-related metabolites. This dysregulation manifests as impaired sucrose partitioning to fruits, reduced biosynthesis of organic acids and pigments, and oxidative degradation of nutritional compounds, ultimately diminishing sensory and nutritional quality. These findings underscore the necessity of precision nitrogen management to balance growth promotion with metabolic equilibrium in horticultural systems (Cheng et al., 2021; Lei et al., 2024b; Mao et al., 2024). The amount of nitrogen application can increase the content of soluble sugar, organic acid, vitamin C and soluble solids. Excessive nitrogen application will reduce the content of vitamin C and soluble solids (Wang et al., 2020; Mao et al., 2024; Li et al., 2024b).

Effects of microbial fertilizers and chemical nitrogen fertilizers on yield of greenhouse tomato

This study demonstrates a nonlinear relationship between microbial inoculation dosage and tomato yield, exhibiting initial enhancement followed by suppression. The observed pattern could be attributed to the plant growth-promoting rhizobacteria (PGPR) properties of *Bacillus subtilis* and *Trichoderma harzianum*. Moderate inoculation (B2 treatment) optimizes yield through dual mechanisms: improving soil nutrient mineralization to enhance bioavailability of nitrogen, phosphorus, and potassium, while simultaneously stimulating root system development for efficient nutrient acquisition. Contrastingly, excessive bacterial application (B3 treatment) triggers ecological imbalances where microbial overproliferation initiates nutrient competition—particularly for available nitrogen—between heterotrophic microorganisms and plant roots. Concurrently, accumulated microbial metabolites may exert phytotoxic effects on root growth. These synergistic stressors ultimately compromise plant nutrient uptake efficiency, thereby constraining yield improvement (Yang et al., 2020; Liu et al., 2024).

These findings align with previous reports on greenhouse tomatoes (Zhao, 2020), maize (Shi et al., 2024), and cotton (Fan et al., 2025), collectively indicating that Zhongnong Fuyuan microbial inoculants exhibit concentration-dependent efficacy across diverse crops, with optimal application thresholds being critical for maximizing agronomic benefits.

The study found that with the increase of N, tomato yield increased first and then decreased. It may be because the yield improvement observed at moderate N application (N3) stems from nitrogen's dual physiological functions: stimulating cellular proliferation and elongation through auxin-mediated pathways while enhancing photosynthetic carbon assimilation by upregulating RuBisCO activity. These synergistic mechanisms promote carbohydrate accumulation in reproductive organs, thereby establishing essential biochemical foundations for fruit development. Conversely, supra-optimal N supply (N4) induces metabolic dysregulation manifested through three interrelated pathways: preferential allocation of photosynthates to luxuriant vegetative growth at the expense of reproductive partitioning, disrupting carbon-nitrogen homeostasis; phytotoxic accumulation of nitrogenous compounds (nitrates/nitrites) that compromise plant defense mechanisms against biotic stressors; rhizosphere acidification and secondary salinization that impair nutrient acquisition through ionic antagonism and microbial community destabilization. Collectively, these N-overload effects create a physiological bottleneck restricting yield enhancement, despite initial growth stimulation (Bello et al., 2024; Niu et al., 2024). Previous studies have found that With the increase of nitrogen application rate, tomato yield increased first and then decreased (Wang et al., 2019; Pandit et al., 2022; Zhang et al., 2024); yield of cucumber increased with the increase of nitrogen application rate (Deng et al., 2023), which was inconsistent with the conclusion of this study. It may be due to the difference in growth characteristics and fertilizer requirement of the two crops. Cucumber is a fast-growing vegetable, and its demand for nitrogen fertilizer is positively correlated with yield within a certain range. Appropriate increase in nitrogen fertilizer can promote plant growth and fruit development, thereby increasing yield. In this study, greenhouse tomatoes may be more sensitive to nitrogen fertilizer demand. Excessive nitrogen application may lead to problems such as soil nutrient imbalance, plant overgrowth or disease increase, but inhibit the improvement of yield (Acharya et al., 2024; Zhou et al., 2025). It may also be due to the differences in experimental design, soil conditions, irrigation methods and the specific scope of nitrogen application in the two studies. These factors work together to lead to different yield response trends.

This study found that the yield of tomato treated with B2N3 combination was significantly higher than that of other treatment groups, which may be due to the synergistic effect of microbial agents and nitrogen fertilizer to optimize the soil micro-environment, promote the nutrient absorption and utilization of tomato plants, and regulate the growth and development of tomato (Fu et al., 2023; Yan et al., 2024). The appropriate amount of *Bacillus subtilis* and *Trichoderma harzianum* (B2 level) applied to the soil can improve the soil structure, increase soil permeability, promote the diversity and activity of soil microorganisms, and thus facilitate the release and transformation of soil nutrients. At the same time, these two microbial agents can also produce a variety of secondary metabolites, such as antibiotics, plant hormones, etc. These substances have a growth-promoting effect on tomato plants, can improve their stress resistance and photosynthesis efficiency, and promote the synthesis and accumulation of carbohydrates. On this basis, the supply of 0.9 times the standard nitrogen application rate (N3) not only meets the basic needs of tomato plants for nitrogen, but also avoids the negative effects of excessive nitrogen application, such as soil nitrogen leaching, plant overgrowth, etc. The appropriate amount of nitrogen supply promoted the nitrogen assimilation and transport of tomato plants, and provided sufficient material basis for the growth and development of fruits. The synergistic effect of microbial agents and nitrogen fertilizer regulated the carbon and nitrogen metabolism balance of tomato plants, optimized the nutrient distribution of fruits, and improved the yield of fruits.

Conclusion

The effects of B and N on the growth, quality, and yield of greenhouse tomato were investigated. This study found that the appropriate amount of B2 treatment was beneficial to the growth of greenhouse tomatoes. For example, the P*n*, LAI, PHT, SDT, root morphological development and dry matter mass of greenhouse tomato under this treatment were significantly better than those B1 or B3 treatment. With the increase of N, the P*n*, LAI, PHT, SDT, root morphological development and dry matter mass of greenhouse tomato increased first and then decreased. The related indexes of fruit shape, fruit flavor, fruit nutrient increased first and then decreased with the increase of B and N, among them, B2 treatment was superior to B1 and B3 on quality of tomato fruit, while N3 treatment was superior to N1, N2 and N4 on quality of tomato fruit, indicating that B2N3 had a positive effect on improving quality of tomato fruit. With the increase of B, the yield of tomato increased first and then decreased. The BNPP showed a decreasing trend; with the increase of N, tomato yield increased first and then decreased. The BNPP showed a decreasing trend. Range analysis shows. The NI of tomato treated with B2N3 was higher than that of B1N1, B1N2, B1N3, B1N4, B2N1, B2N2, B2N4, B3N1, B3N2, B3N3 and B3N4 by about 59.85% and 40.13%, 32.39% and 20.38%, 34.57% and 5.68%, 55.76% and 12.08%, 26.98% and 25.31%, 15.42% and 3.44%, 2.97% and 4.73%, 42.50% and 36.32%, 22.02% and 18.09%, 3.64% and 9.77%, 6.12% and 12.44%. TOPSIS method was used to evaluate the comprehensive benefits of tomato total dry matter quality, fruit quality, yield, bacterial nitrogen partial productivity and net income. The model further confirmed the advantages of B2N3 treatment in comprehensive benefits. Considering comprehensively, the combination mode of B2N3 application amount and nitrogen application levels is adopted in greenhouse tomato planting in greenhouse. This combination can not only ensure the high yield and high quality of tomato, but also effectively improve the economic benefits. The conclusion of this study provides data support for fertilizer saving and yield increase of tomato in greenhouse.

Declarations. Availability of data and materials: The data and materials in the study are available from the corresponding author on reasonable request.

Competing interests. The authors declare that they have no competing interests.

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