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Research Article

Effects of Fertilization Frequency and Amount on the Chemometric Characteristics, Physiology, and Yield of Tomato Under Substrate Cultivation

Enling Ji, Qianqian Di, Qingjie Du, Meng Li and Huaijuan Xiao

Department of Protected Agriculture Science and Engineering, College of Horticulture, Henan Agricultural University, Zhengzhou, China

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Corresponding Author:
Qingjie Du
Department of Protected Agriculture Science and Engineering, College of Horticulture, Henan Agricultural University, Zhengzhou, China
Email: duqj91@163.com

Abstract: This study examined the effects of fertilization frequency and quantity on growth, yield, and quality of tomatoes under substrate cultivation. A factorial experiment evaluated two fertilization frequencies (every 5 or 10 days) and three fertilization levels (15.69, 31.38, or 62.76 kg·ha⁻¹), along with an unfertilized control. Plants were assessed for growth and development, photosynthetic pigment content, gas exchange parameters, nutrient uptake, fruit quality attributes, and yield. Fertilization every 10 days at 62.76 kg·ha⁻¹ (T8) produced the highest nutrient content in both substrate and plant tissues. Compared with the control, fertilization every 5 days at 31.38 kg·ha⁻¹ (T4) significantly increased soluble sugar and soluble solids content in tomato fruits while decreasing organic acid content, without significantly affecting vitamin C content or yield. Comprehensive evaluation using five analytical methods-principal component analysis (PCA), VIKOR method, TOPSIS analysis, membership function analysis, and grey relational analysis-identified T4 as the optimal treatment demonstrating superior overall performance. These findings provide a theoretical basis and practical guidance for scientific fertilization management to achieve high-quality, high-yield, and sustainable tomato production under substrate cultivation systems. The results support precision nutrient management strategies for soilless vegetable production.

Keywords: Tomato, Substrate Cultivation, Fertilization Frequency, Nutrient Management, Fruit Quality, Comprehensive Evaluation, Multi-Criteria Analysis, Soilless Culture

Introduction

Tomato (*Solanum lycopersicum* L.) is a major vegetable crop that is widely and globally cultivated (Amini and 2005; Averello *et al*., 2025; Jin *et al*., 2022). In 2023, China produced 7.02 × 10⁷ tons of tomatoes on 1.16 × 10⁶ ha of land, positioning it as a substantial contributor to global vegetable production (FAO, 2023; Szabo *et al*., 2025). In recent years, facility agriculture has rapidly developed, while substrate cultivation technology has gained popularity in large-scale tomato production owing to its high resource utilization efficiency and environmental benefits (Gruda, 2019; Qin *et al*., 2024). Unlike traditional soil cultivation, crops in substrate cultivation systems depend entirely on artificial fertilization for nutrients. Therefore, scientific and rational fertilization management is crucial for ensuring the production of tomatoes with high quality and high yields.

Extensive studies on crop fertilization management show that proper fertilization improves soil physicochemical properties and enhances nutrient uptake in several crops, such as mini Chinese cabbage (Dan *et al*., 2024; Xiang *et al*., 2018). Nutrient uptake is a dynamic process influenced by root architecture, soil pH, and nutrient mobility. Plants absorb essential elements (e.g., N, P, K) through active and passive transport mechanisms, which is optimized under balanced fertilization (Barłóg *et al*., 2022; Forde, 2014; Li *et al*., 2016; Liu *et al*., 2020). In cotton, reducing fertilization frequency during the crop's initial flowering stage decreases production costs but maintains yields (Luo *et al*., 2020), while a 10% increase in fertilizer amount in tomatoes grown on substrate enhances their biomass, oxidation activities, and yields (Melissa *et al*., 2022; Xiao *et al*., 2020). However, excessive fertilization disrupts ion homeostasis, leading to nutrient imbalances that impair absorption efficiency and increase oxidative stress (Munns and Tester 2008; Ren *et al*., 2022; Shi *et al*., 2023). This can also exacerbate substrate salinity, further inhibiting root function (Haj-Amor *et al*., 2022). Despite these previous findings on the impact of the frequency and amount of fertilization, most relevant published studies have focused on either a single fertilization period or a single fertilization factor. Therefore, the mechanisms by which different fertilization frequencies and amounts affect substrate-grown tomatoes, as well as their relationships with yield and quality, require further investigation.

This study analyzed differences in tomato growth parameters, physiological indicators, yield, and quality metrics under different fertilization frequencies and amounts to identify optimal fertilization strategies for substrate-cultivated tomatoes and provide an empirical foundation for precision fertilization practices. These findings contribute to promoting environmentally sustainable development of protected vegetable production.

Materials and Methods

Study Site

This experiment was conducted in a plastic greenhouse in Zhengzhou, Henan, China (113°35′27″E, 34°51′52.12″N) from March to July 2024 using a commercial substrate with a pH of 6.33, Electrical Conductivity (EC) of 4.07 $\mu S\cdot cm^{-1}$, Total Organic Carbon (TOC) content of 23.64 $mg\cdot g^{-1}$, total Nitrogen (N) content of 19.7 $g\cdot kg^{-1}$, total Phosphorus (P) content of 13.9 $g\cdot kg^{-1}$, available N content of 774.90 $mg\cdot kg^{-1}$, and available P content of 139.90 $mg\cdot kg^{-1}$.

Experimental Design

The seeds of the ‘Yuyiyou 5’ tomato variety from Henan Yuyi Seed Industry Technology Development Co., Ltd. (Zhengzhou, China) were germinated in substrate in cultivation tanks measuring 15 cm deep by 15 cm wide and lined with plastic film. Tomato seedlings were then transplanted according to a randomized block design at the four-leaf stage on March 21, 2024 and harvested on July 9, 2024. Tomatoes were planted in plots measuring 3.5 × 1.3 m, with each plot containing 16 plants arranged in a single row. The tomato growth period consisted of a 30-d vegetative phase, including planting to flowering and fruit set of the first panicle (March 21 to April 20, 2024) followed by an 80-d fruiting period (April 21 to July 9, 2024). Urea (nitrogen source), monoammonium phosphate (phosphorus source), and potassium nitrate (potassium source) were mixed according to a ratio of 1:2:1 and applied through integrated irrigation at a rate of 15.69, 31.38, and 62.76 $kg\cdot ha^{-1}$ once every 5 or 10 d, starting a week after transplantation (Table 1). Thus, a total of nine treatments were applied in triplicate, which included eight different fertilization treatments (T1 to T8), with unfertilized plants as the control treatment.

Plant Morphological Measurements and Yield Determination

Growth parameters were measured at 0, 20, 40, and 60 d after treatment initiation. For each treatment, six tomato plants were randomly selected; all leaves on each selected plant were counted, and both the height of the plant from the soil surface to its apical growth point and its stem diameter 1 cm above the surface were measured. Fruits were promptly harvested upon ripening, and the total yield from each experimental plot was recorded.

Table 1: Fertilization schemes for different growth stages of tomato

Treatment	Planting to flowering and fruit set of the first panicle		Fruiting period		Total amount of fertilization ($kg\cdot ha^{-1}$)
	Fertilization frequencies	Fertilization level ($kg\cdot ha^{-1}$)	Fertilization frequencies	Fertilization level ($kg\cdot ha^{-1}$)	
CK	0	0	0	0	0
T1	once every 5 days, 6 times in total	15.69	once every 5 days, 14 times in total	15.69	313.80
T2	once every 5 days, 6 times in total	15.69	once every 5 days, 14 times in total	31.38	533.46
T3	once every 5 days, 6 times in total	31.38	once every 5 days, 14 times in total	15.69	407.94
T4	once every 5 days, 6 times in total	31.38	once every 5 days, 14 times in total	31.38	627.60
T5	once every 10 days, 3 times in total	31.38	once every 10 days, 7 times in total	31.38	313.80
T6	once every 10 days, 3 times in total	31.38	once every 10 days, 7 times in total	62.76	533.46
T7	once every 10 days, 3 times in total	62.76	once every 10 days, 7 times in total	31.38	407.94
T8	once every 10 days, 3 times in total	62.76	once every 10 days, 7 times in total	62.76	627.60

Determination of Chlorophyll Content and Photosynthetic Parameters

Thirty-one days after transplanting, the net Photosynthetic rate (P_n), Transpiration rate (T_r), stomatal conductance (G_s), and intercellular carbon dioxide (CO_2) Concentration (C_i) of the tomato plants were measured using a photosynthetic instrument (LI-COR 6400XT, LI-COR, Lincoln, NE, USA). The apparent CO_2 utilization rate (CUE_{app}) was obtained as P_n/C_i, while the instantaneous Water Use Efficiency (WUE_t) was calculated as P_n/T_r as described previously (Zhang *et al*., 2024). The middle leaves of tomato plants were also collected for determination of their contents of chlorophyll a and b, total chlorophyll (a + b), and carotenoids as described by Muradoglu *et al*. (2015). Each treatment was replicated six times.

Nutrient Analysis in Tomato Plants and Cultivation Substrate

The total N content in roots, stems, leaves, fruits, and cultivation substrates of tomato plants was determined using a K1160 automatic Kjeldahl analyzer (Hanon Advanced Technology Group Co., Ltd. Jinan, China). The N and TOC contents in the plant organs and substrates were determined by colorimetry analysis (Koenig and Johnson 1942) and potassium dichromate oxidation-spectrophotometry (Luo and Wang. 2014), respectively.

Determination of Tomato Fruit Quality

After the third truss of fruits reached maturity, uniformly ripened tomato fruits were harvested, and their vitamin C content was determined as described by Gao (2006). The contents of total soluble solids, total soluble sugar and organic acid were quantified using a digital refractometer (PAL-1 portable digital refractometer, Shanghai INESA Physico-Optical Instrument Co., Ltd. Shanghai, China), anthrone colorimetry (Zhang *et al*., 2021), and acid-base titration (Yu *et al*., 2023), respectively. Soluble proteins and nitrates were measured using Coomassie brilliant blue G-250 staining and the concentrated sulfuric acid-salicylic acid solution method, respectively.

Comprehensive Evaluation

Excel 2019 (Microsoft Corp., Redmond, WA, USA) was used for data collation, and multiple analytical methods, including principal component analysis (Tang *et al*., 2021), the VIKOR method (Yang and Chen. 2023), TOPSIS analysis (Çelikbilek *et al*., 2020), membership function analysis (Singh *et al*., 2024), and grey correlation analysis (Sun *et al*., 2022), were employed for comprehensive evaluation of tomato gas exchange parameters, fruit quality and yield.

Data Analysis

Statistical analysis was performed using SPSS 27.0 (IBM Corp. Armonk, NY, USA), with the least Significant Difference (LSD) test *($P < 0.05$)* used to assess significant differences among treatments while correcting for multiple comparisons. All figures were generated using Origin 2022 (Origin Lab, Northampton, MA, USA).

Results

Effects of Different Fertilization Frequencies and Amounts on Substrate Element Content

The T8-treated substrate had the highest TOC content, which was significantly increased by 52.80% compared to the unfertilized control, while the other treatments showed no significant differences from the control. The TN content of T5- and T8-treated substrates was significantly higher than those of T3-, T6-, and T7-treated substrates, while the TP content did not differ significantly among the treatments. The C/N and N/P ratios of the T8 treatment were significantly higher than those of the T3 and T7 treatments. The C/P ratios of the T4- and T8-treated substrates were significantly higher than those of the control and the T1-, T3-, and T7-treated substrates. Of all the treatments, only T8-treated plants showed significantly increased TOC content in the substrate, as well as an increased C/P ratio (Table 2).

Effects of Different Fertilization Frequencies and Amounts on Tomato Growth and Development

During the early stage of tomato growth (20 d), the plant height of T4- and T5-treated plants was significantly higher than those of the unfertilized control, while the other treatments showed no significant differences from the control. The stem diameter of T6-treated plants was significantly reduced by 14.82% compared to the control, while the number of leaves of T3-treated plants was significantly higher than those of the control. When the growth cycle reached 40 d, plant height of the control was significantly lower than those of all the other treatments, while the stem diameter of T4-, T7-, and T8-treated plants was significantly higher than those of the control by 26.07, 18.30, and 19.17%, respectively. However, after 60 d of tomato growth, only the height of T4-, T5-, T6-, and T7-treated plants was significantly higher than those of the control, with the stem diameter and leaf number showing non-significant differences among the treatments (Fig. 1).

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Table 2: Effects of fertilization frequency and amount on the contents of substrate elements.

Treatment	TOC ($g\cdot kg^{-1}$)	TN ($g\cdot kg^{-1}$)	TP ($g\cdot kg^{-1}$)	C/N	C/P	N/P
CK	9.52±1.17bcd	8.15±0.24abc	1.04±0.05a	1.17±0.17ab	9.25±1.77cd	7.85±0.40ab
T1	8.99±1.56cd	8.47±0.31ab	1.03±0.04a	1.08±0.29b	8.61±2.02cd	8.24±0.57ab
T2	10.03±1.47bcd	8.10±0.39abc	1.01±0.01a	1.30±0.26ab	10.45±2.04bcd	8.06±0.32ab
T3	7.35±1.01d	8.02±0.07bc	1.03±0.04a	0.94±0.17b	7.26±1.07d	7.80±0.34b
T4	12.32±1.58ab	8.33±0.21ab	1.01±0.02a	1.56±0.28a	12.84±2.05ab	8.28±0.17ab
T5	11.02±0.21bc	9.12±0.38a	1.01±0.01a	1.23±0.05ab	11.17±0.11abc	9.07±0.30a
T6	10.93±0.37bc	7.98±0.24bc	1.00±0.01a	1.36±0.10ab	10.82±0.42bc	7.98±0.31ab
T7	7.86±0.50d	7.25±0.22c	0.99±0.01a	1.08±0.10b	7.90±0.75cd	7.31±0.26b
T8	14.54±0.06a	9.12±0.75a	1.01±0.01a	1.61±0.13a	14.42±0.24a	9.07±0.83a

Note: Different lowercase letters within the same column indicate significant differences between treatments ($P < 0.05$). This notation system applies to all subsequent tables and figures. TOC: total organic carbon, TN: total nitrogen, TP: total phosphorus.

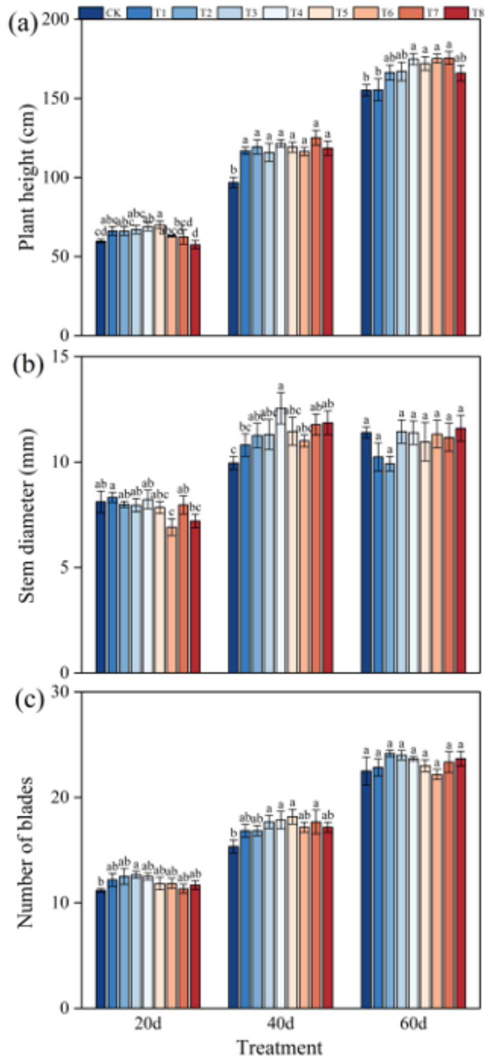


Fig. 1: Effects of different fertilization frequencies and amounts on tomato growth. Different lowercase letters on the column indicate significant differences between treatments ($P < 0.05$)

Effects of Different Fertilization Frequencies and Amounts on Tomato Photosynthetic Pigments

The unfertilized plants exhibited similar contents of chlorophyll a with those of plants under T2, T3, and T5 treatments but had significantly reduced contents of chlorophyll a, chlorophyll b, total chlorophyll, and carotenoids compared to those in the T1, T4, and T8 treatments, indicating that the T1, T4, and T8 treatments strongly promoted the synthesis and accumulation of photosynthetic pigments in tomato. Additionally, the contents of chlorophyll b, total chlorophyll, and carotenoids were similar in other treatments (Table 3).

Effects of Different Fertilization Frequencies and Amounts on Gas Exchange Parameters of Tomato

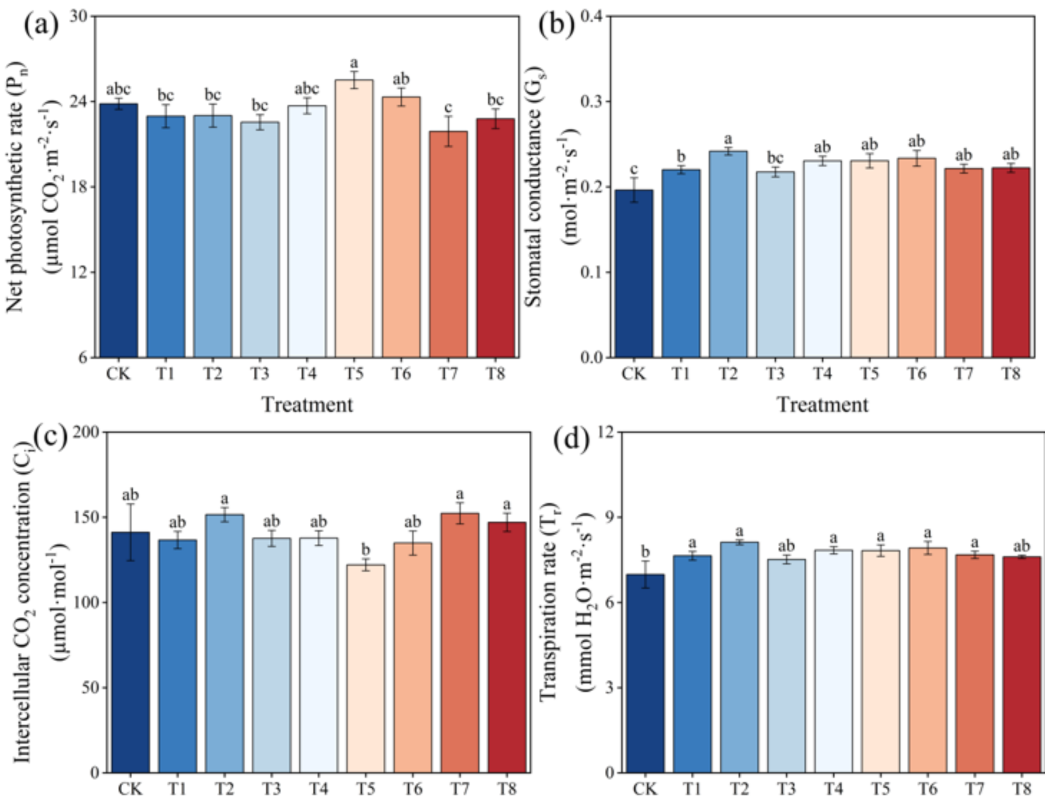
The P_n value under the T5 treatment was significantly higher than those under the other treatments but similar to those under the control, T4, and T6 treatments, while the G_s value in all treatments except T3 exhibited significantly higher values than that of the control. The T_r values of T3- and T8-treated tomatoes were not significantly different, while both were significantly higher than that of the control. The WUE_t values in the T2 and T7 treatments were significantly lower than those in the control by 12.36% and 12.05%, respectively, while C_i and CUE_{app} values were not significantly different between the fertilized treatment and unfertilized control (Fig. 2).

Effects of Different Fertilization Frequencies and Amounts on Chemometric Characteristics of Tomato Plants

Non-significant differences were observed in the contents of TOC, TN, and TP between the roots of fertilized tomatoes and unfertilized control tomatoes as well as in the stem TOC between the control treatment and the T2, T3, and T6 treatments. The TN content in stems of T5, T6, and T7 treatments was significantly lower than those of the control, by 25.33%, 11.03%, and 21.16%, respectively, while the TP content in stems of T1-treated plants was significantly higher relative to all other treatments. The contents of leaf TOC in the T8 treatment was significantly higher, by 50.44% compared to that in the control, while the content of leaf TN of the controls was significantly lower than those in the T1, T3, T6 and T7 treatments. The content of leaf TP was significantly lower than those of the T1 and T4 treatments, while the content of fruit TOC in T4, T5, T6, and T7 treatments was significantly lower than those of the controls (Fig. 3). The C/N and C/P ratios in the roots of T5-treated tomatoes were significantly lower than those of the controls by 47.45% and 47.40%, respectively, while non-significant differences were observed in the N/P ratio between the roots of fertilizer-treated plants and the unfertilized control. The stem C/N ratio in T5, T7, and T8 treatments was significantly higher than those in the unfertilized control, while the stem C/P ratio in T5 and T8 treatments was significantly higher than those in the unfertilized controls. However, the N/P ratio significantly decreased in T5, T6, and T7 treatments compared to the control. Simultaneously, the C/N and C/P ratios of leaves in the T8 treatment significantly increased by 64.64% and 65.56%, respectively, compared with the control, while the C/N and C/P ratios of tomato fruits in the T7 treatment significantly decreased.

Table 3: Effects of different fertilization frequencies and amounts on the photosynthetic pigments of tomato

Treatment	Chlorophyll a ($mg \cdot g^{-1}$)	Chlorophyll b ($mg \cdot g^{-1}$)	Chlorophyll (a+b) ($mg \cdot g^{-1}$)	Carotenoids ($mg \cdot g^{-1}$)
CK	0.582±0.01d	0.166±0.008d	0.748±0.013d	0.156±0.003d
T1	0.773±0.02a	0.202±0.005a	0.975±0.024a	0.188±0.007a
T2	0.655±0.022cd	0.171±0.005d	0.827±0.027cd	0.162±0.006bcd
T3	0.654±0.062cd	0.171±0.013d	0.825±0.076cd	0.157±0.016cd
T4	0.737±0.024ab	0.192±0.005abc	0.929±0.029ab	0.179±0.007abc
T5	0.660±0.013bcd	0.176±0.004cd	0.836±0.017bcd	0.163±0.003bcd
T6	0.690±0.010bc	0.183±0.002abcd	0.873±0.012bc	0.171±0.004abcd
T7	0.685±0.018bc	0.182±0.005bcd	0.867±0.023bc	0.175±0.005abcd
T8	0.731±0.030abc	0.200±0.008ab	0.931±0.037ab	0.182±0.009ab



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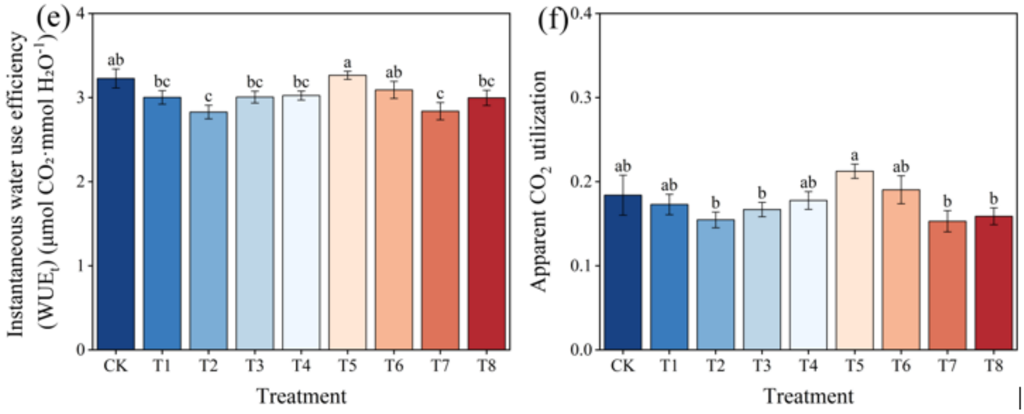
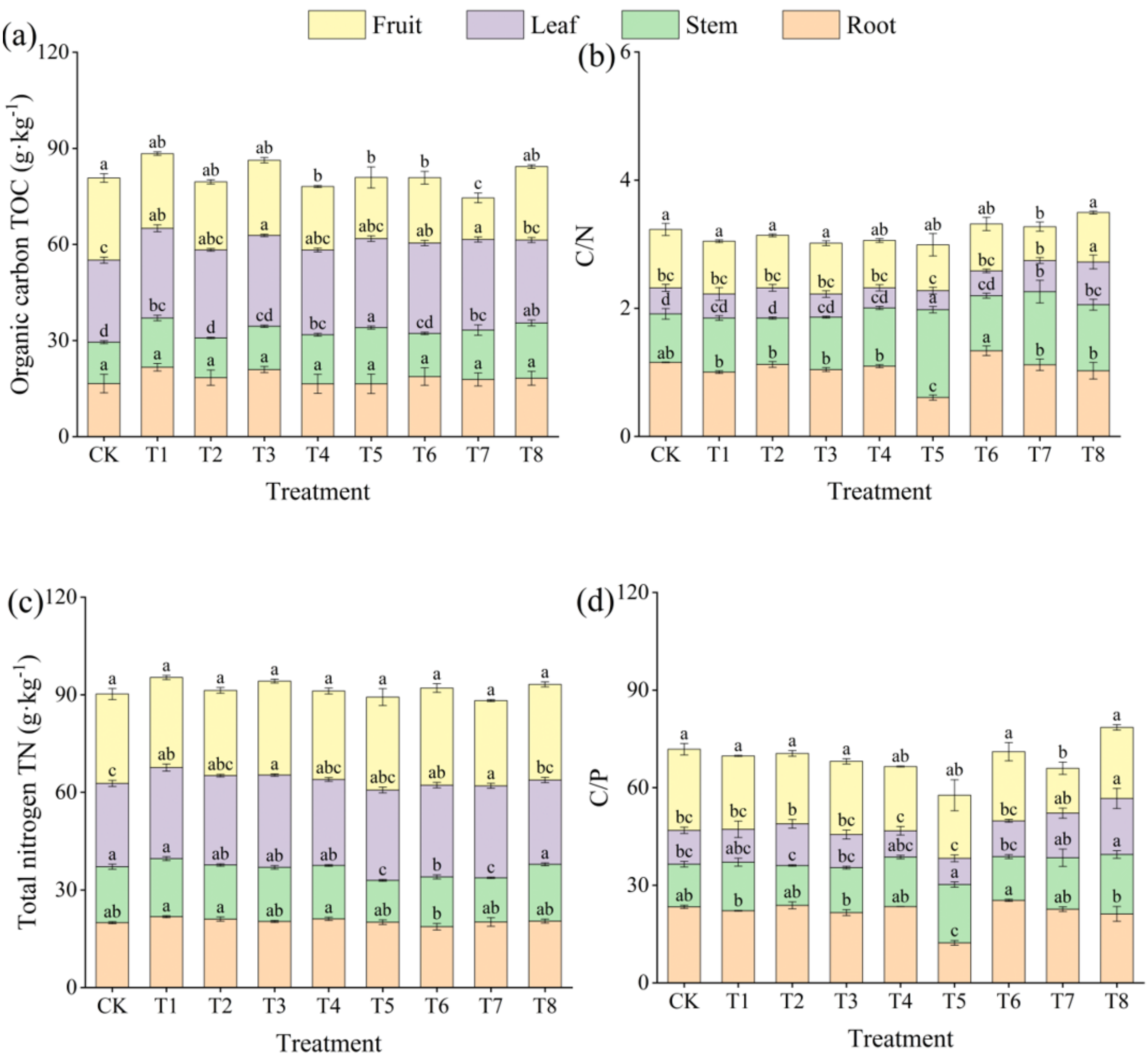


Fig. 2: Effects of different fertilization frequencies and amounts on gas exchange parameters of tomato (P<0.05)



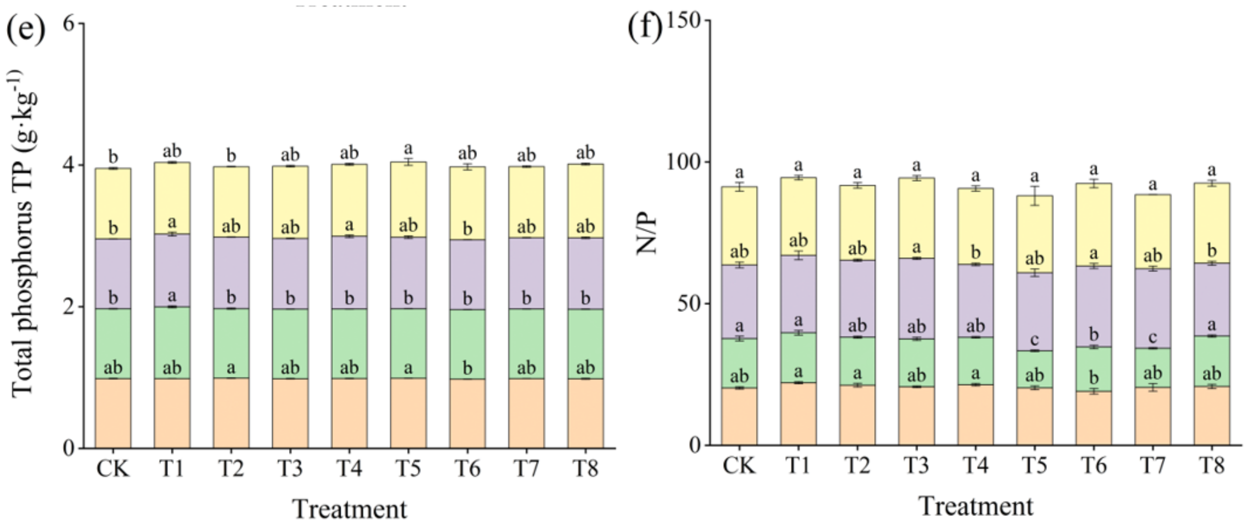


Fig. 3: Effects of different fertilization frequencies and amounts on tomato chemometric characteristics (P<0.05)

Effects of Different Fertilization Frequencies and Amounts on the Tomato Quality Index

The contents of soluble sugar in T7-treated tomatoes significantly increased, by 52.44%, compared with the control, while the contents of soluble protein in T1-, T4-, and T7-treated plants were not significantly different from the control. The unfertilized control plants had significantly reduced contents of soluble solids relative to those in T3- and T4-treated fertilized plants but greater soluble solids content than those in the T6- and T8-treated fertilized tomatoes. The vitamin C content in the control was significantly lower than those in T3- and T5-treated fertilized tomatoes, while the organic acid content was significantly lower than those in T4- and T8-treated fertilized plants. However, non-significant differences were observed in nitrate content between the fertilized plants and unfertilized control plants (Fig. 4).

Effects of Different Fertilization Frequencies and Amounts on Tomato Yield

The yield of the T2-treated plants was significantly higher, by 14.38% and 14.44%, respectively, relative to those in the controls and T8 treatments, but was not significantly different among the T3, T4, T6, and control treatments. Nevertheless, the yields of T3-, T4-, and T6-treated fertilized tomatoes increased yield by 12.87%, 13.18%, and 11.59% higher than those in the unfertilized control, respectively. Additionally, the yield in the T1 and T5 treatments was only 5.46 and 4.52% higher than those in the unfertilized controls (Fig. 5).

Correlation Analysis

The results (Fig. 6) demonstrated a significant and positive correlation of Gs with Tr ($P < 0.001$), and a significant but negative correlation of Pn with Ci ($P < 0.01$). Additionally, a significant but negative correlation was observed between soluble protein content and vitamin C content ($P < 0.05$). These results revealed varying degrees of correlation between tomato quality indicators and yield under different fertilization treatments, indicating potential information overlap among some indicators. Therefore, to avoid invalid analysis of results caused by redundant information between indicators, it was necessary to use appropriate statistical methods to ensure the accuracy and scientific validity of the evaluation results (Wang *et al*., 2022).

A Comprehensive Evaluation of the Tomato Growth Index Under Different Fertilization Frequencies and Amounts

A smaller profit ratio value calculated by the VIKOR method indicates a better comprehensive quality and yield of a treatment, while a larger comprehensive evaluation value calculated by the TOPSIS method, grey correlation analysis, membership function method, and principal component analysis indicates a better overall performance. The T4 treatment was ranked first according to its relative proximity, interest ratio, membership function value, correlation degree and comprehensive score, fully demonstrating its superior comprehensive performance. In contrast, control and T5 treatments ranked lower, while T2 treatment showed relatively better comprehensive performance (Table 4). In summary, the combination of fertilization amount and frequency under the T4 treatment was the most suitable and could best promote the healthy growth of tomato plants and improve their fruit qualities and yields.

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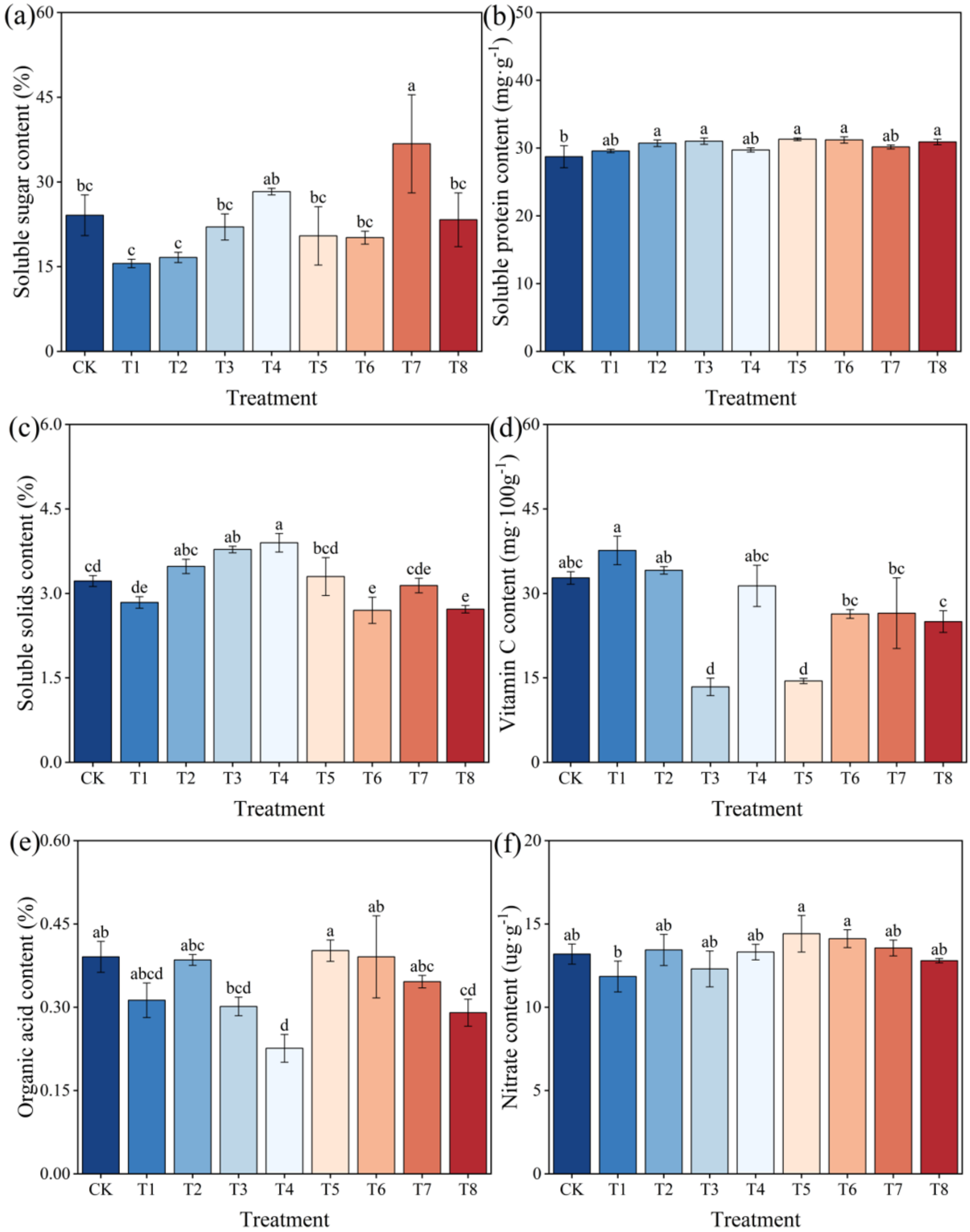

Fig. 4: Effects of different fertilization frequencies and amounts on tomato quality (*P*<0.05)

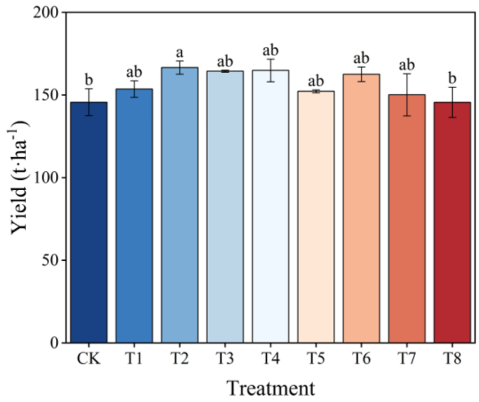

Fig. 5: Effects of different fertilization frequencies and amounts on tomato yield (*P*<0.05).

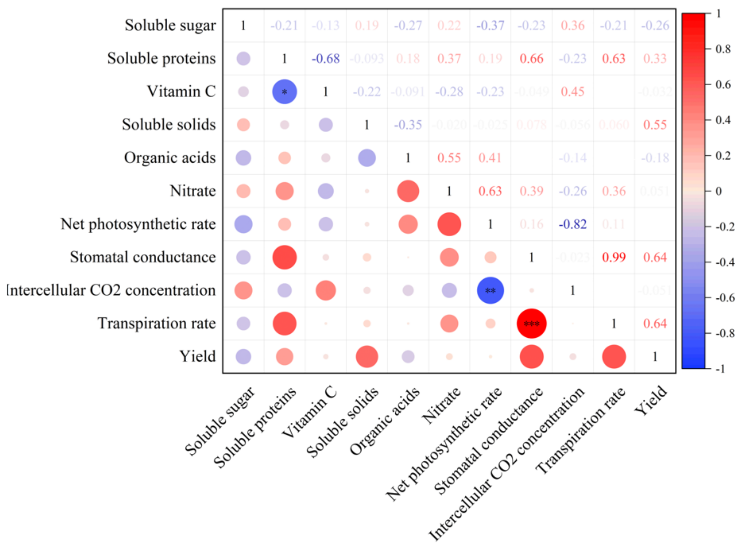

Fig. 6: Pearson correlation analysis of tomato quality indexes treated with different fertilization frequencies and amounts. *indicates a significant difference at $P < 0.05$ and **indicates significant difference at $P < 0.01$

Table 4: Comprehensive evaluation of tomatoes under different fertilization frequencies and amounts

Treatment	TOPSIS method		VIKOR Method		Membership Function Method		Grey Relational Analysis		Principal Component Analysis	
	Relative Approach Degree	Rank	Profit Ratio	Rank	Subordinate Function Values	Rank	Correlation Degree	Rank	Comprehensive Score	Rank
CK	0.36	9	1.00	9	0.42	6	0.50	6	0.25	9
T1	0.46	6	0.78	6	0.48	4	0.59	4	0.41	6
T2	0.53	2	0.49	2	0.53	3	0.61	3	0.68	2
T3	0.52	3	0.69	3	0.41	7	0.51	5	0.65	3
T4	0.66	1	0.00	1	0.74	1	0.70	1	0.77	1
T5	0.43	8	0.85	8	0.25	9	0.44	9	0.58	4
T6	0.45	7	0.75	5	0.36	8	0.47	8	0.55	5
T7	0.49	4	0.75	4	0.58	2	0.61	2	0.38	7
T8	0.46	5	0.79	7	0.44	5	0.49	7	0.33	8

Discussion

Effects of Fertilization Frequency and Amount on Element Content and Chemometric Characteristics

Fertilization frequency and application rates significantly influence nutrient element content and proportions in growth substrates. In this study, T8 treatment significantly enhanced the TOC content in the substrate and tomato stems and leaves. l "This pattern suggests that reduced nutrient supply under low-frequency fertilization provides insufficient plant nutrition, thus triggering source-sink relationship reconstruction. Consequently, plants adjust their carbon allocation, thereby favoring the accumulation of photosynthetic products in vegetative tissues rather than supporting new tissue development (Ven *et al*., 2020). Notably, TP content in the substrate and tomato roots and fruits remained relatively unaffected across all fertilization treatments, contrasting with findings reported by Abdoun *et al.* (2023), which may be explained by P characteristics. For example, P exhibits poor mobility and undergoes rapid fixation after its application, resulting in minimal fluctuation in TP content (Grenon *et al*., 2021). Furthermore, despite the existence of P-solubilizing microorganisms in substrates, alterations in fertilization frequency do not substantially modify microbial community structure, thereby contributing to stable P levels (Bourak *et al*., 2023; Tao *et al*., 2023).

The T4 and T8 treatments significantly elevated substrate C/N and C/P ratios compared to the unfertilized control. However, the examination of chemometric characteristics across all plant organs revealed that the T4 treatment maintained C/N, C/P, and N/P ratios comparable to those of the unfertilized control, while the T8 treatment significantly altered C/N and C/P ratios in the roots and stems. These findings suggest that an appropriate fertilization frequency satisfies growth requirements for both plant and substrate nutrient cycling (Rubio-Asensio and Intrigliolo. 2024), while low-fertilization frequency potentially alters nutrient transformation processes, affecting carbon retention and nitrogen availability (Dobbratz *et al*., 2022; Li *et al*., 2021; Massa *et al*., 2018), thereby reducing the available N and subsequently increasing C/N ratios.

Effects of Fertilization Frequency and Amount on Photosynthetic Pigments and Gas Exchange Parameters

Photosynthetic pigments, including chlorophyll and carotenoids, play crucial roles in plant productivity. Since N is a primary component of chlorophyll, its sufficient supply is typically associated with elevated chlorophyll content (Cechin *et al*., 2022). In this study, T1, T4, and T8 treatments significantly increased tomato photosynthetic pigment content, confirming that these strategies effectively met N requirements through either high-frequency application or increased application rates. Additionally, changes in substrate C/N ratios may influence nutrient cycling dynamics, thereby affecting N availability and enabling more efficient plant N uptake during specific developmental stages (Powlson *et al*., 2015), which may further support the current findings.

Gas exchange parameters are essential indicators of photosynthetic capacity. In this study, T1, T4, T5, and T6 treatments showed significantly higher G_s and T_r values compared to the unfertilized control, while their P_n, C_i, WUE_t, and CUE_{app} values were not significantly different from those of unfertilized controls. Ivanov *et al.* (2022) reported that despite enhanced light absorption resulting from increased photosynthetic pigment content, insufficient coordination between light-dependent and light-independent reactions prevents significant changes in P_n. Furthermore, low-frequency fertilization induces N limitation, triggering efficient utilization mechanisms that promote the synthesis of photosynthetic pigments, but constraining overall photosynthetic capacity, resulting in stable C_i and WUE_t values (Elhindi *et al*., 2016; Matić *et al*., 2021). Thus, the consistent CUE_{app} values in tomatoes potentially indicate a shift in carbon allocation strategy, prioritizing structural component synthesis over growth, and resulting in increased photosynthetic products without observable changes in utilization efficiency.

Effects of Fertilization Frequency and Amount on Growth, Quality, and Yield of Tomatoes

The frequency and amount of fertilization also significantly affected tomato growth, quality, and yield throughout its entire growth cycle in this study. For example, the T4 and T5 treatments significantly enhanced plant height at 20 and 60 d after treatment initiation, while T4, T7, and T8 treatments significantly increased stem diameter at 40 d compared to unfertilized controls. T4 treatment likely promoted root development through the nutrients provided by high-frequency fertilization, subsequently enhancing plant height and stem diameter, while T5, T7, and T8 treatments may have altered the microbial community structure through low-frequency fertilization, thereby indirectly influencing tomato development (Ali *et al*., 2022; Huang *et al*., 2019; Xun *et al*., 2016).

The T3 and T4 treatments significantly increased the contents of soluble solids compared to the unfertilized control, with only the T4 treatment significantly reducing the organic acid content. Though only the T2 treatment yielded significantly more fruits than the unfertilized control, the T4 treatment increased yield by 13% compared to the control. These results may be related to the elevated substrate nutrient content, though balanced fertilization practices could be more effective in enhancing quality parameters (Zhou *et al*., 2022). High-frequency moderate fertilization maintains dynamic nutrient equilibrium in the substrate, preventing the salt accumulation and nutrient loss associated with single large-volume fertilizer applications, while promoting suitable EC and pH values (Beckmann-Cavalcante *et al*., 2013; Ezziddine *et al*., 2021). Moreover, a stable nutrient supply improves physical and chemical substrate properties, and maintains optimal aeration and moisture conditions that promote root development and nutrient absorption (Antônio ZANÃO JÚNIOR *et al*., 2022; Mir *et al*., 2013). Appropriate fertilization strategies also provide stable environmental conditions in the substrate that can enhance organic matter decomposition and nutrient release processes (Sharma *et al*., 2025). Therefore, the optimization of the substrate environment directly influences nutrient absorption and transport efficiency in tomatoes, ultimately improving fruit soluble sugar and solid contents, while reducing organic acid levels, thus enhancing overall fruit quality (Li *et al*., 2023).

In this study, multi-dimensional evaluation methods, including TOPSIS, VIKOR, and grey correlation analysis, were employed to comprehensively assess tomato yield and quality, resulting in the identification of the T4 treatment as optimal for tomato growth. This multi-method approach mitigates potential bias associated with any single evaluation technique, thereby providing a more reliable scientific foundation for precision fertilization practices. However, it should be noted that our experiment was conducted at a single location under greenhouse conditions. Future research should include multi-location trials across diverse environmental conditions to validate and extend these results, enhancing their applicability for broader commercial implementation.

Conclusion

This study investigated the effects of fertilization frequency and application rates on substrate-cultivated tomatoes. The results demonstrated that fertilization every 5 d at a rate of 31.38 $kg \cdot ha^{-1}$ in the T4 treatment significantly enhanced the substrate C/N and C/P ratios, fruit soluble sugar and solid contents, photosynthetic pigment contents, stomatal conductance, and transpiration rate and reduced the organic acids in fruits, but did not affect vitamin C content and yield, compared to those in the unfertilized control. Comprehensive evaluation using five different analytical methods revealed that applying fertilizer at a rate of 31.38 $kg \cdot ha^{-1}$ once every 5 d optimized substrate element composition, promoted plant growth, and improved tomato fruit quality. These findings provide an empirical basis and practical guidance for scientific and reasonable fertilization management to achieve high-quality, high-yield, and sustainable tomato production.

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Author Contributions

Enling Ji: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft.
Qianqian Di, Meng Li and Huaijuan Xiao: Investigation, Formal analysis, Validation.
Qingjie Du: Conceptualization, Methodology, Investigation, Supervision, Writing – review & editing.

Ethics

This article is original and contains unpublished material. The corresponding author confirms that all of the other authors have read and approved the manuscript and no ethical issues involved.

Conflict of Interest

The authors declare no conflicts of interest.

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