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EFFECTS OF OPTIMIZED FERTILIZATION ON THE GROWTH OF OPEN-FIELD TOMATO AND THE SOIL ENVIRONMENT

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Abstract

Field experiments were conducted in 2024 and 2025 in suburban Beijing to evaluate fertilization strategies for improving yield, fertilizer use efficiency, and soil quality in open-field tomato production under uniform irrigation conditions. Four treatments were established: T1 (no fertilizer), T2 (conventional fertilization), T3 (optimized fertilization), and T4 (optimized fertilization combined with a soil conditioner). Differences in soil nutrient status, plant growth, yield, and fruit quality were observed among treatments. Compared with the other treatments, T4 consistently improved soil fertility, enhanced yield formation, and promoted fruit quality, while also increasing fertilizer use efficiency. Specifically: (1) The contents of available phosphorus (AP), available potassium (AK), total nitrogen (TN), ammonium nitrogen (NH_4^+-N), and nitrate nitrogen (NO_3^--N) in the 0–60 cm soil profile, together with soil organic matter (OM), were significantly increased. (2) The average yield over the two-year period was increased by 26.21% relative to T2. (3) Relative to T2, the two-year average fruit soluble solids content (SSC), sugar–acid ratio (SAR), and vitamin C (VC) content were increased by 9.99%, 8.11%, and 26.55%, respectively. However, the two-year averages masked year-to-year differences: SSC rose significantly only in 2025, SAR only in 2024 ($p<0.05$), whereas VC improved in both years. (4) Relative to T2, the utilization efficiencies of nitrogen, phosphorus, and potassium fertilizers were comprehensively enhanced, particularly in terms of productivity and agronomic efficiency. The agronomic efficiency of potassium fertilizer was increased by an average of 1.76-fold over the two-year period. This study provides a basis for improving the yield and quality of open-field tomatoes in the suburbs of Beijing, while promoting efficient use of agricultural resources.

Key words: Open-field tomato; Soil quality; Yield and quality; Fertilizer use efficiency; Optimized fertilization

Introduction

China ranks first in global vegetable production. The country uses 41.2% of the world's vegetable planting area but produces 50.9% of the global total harvest (Anon., 2022). Many vegetable crops have shallow roots, which cannot take up nutrients efficiently. In intensive farming, growers therefore tend to apply more fertilizer than needed. Over-applying fertilizer does more than cut nutrient efficiency. It also harms the environment: more greenhouse gases, eutrophied surface waters, and nitrate building up in groundwater (Huang *et al*., 2017). In this context, optimizing fertilization strategies to achieve a balance among yield, quality, and environmental sustainability have become increasingly important.

Tomato (*Solanum lycopersicum* L.) ranks among the most widely grown fruit vegetables worldwide. China is not only the largest producer but also the biggest consumer (Xu *et al*., 2025). In China of open-field cultivation, vegetables occupy over 70% of the total vegetable planting area (Guo *et al*., 2021). Earlier work has shown that optimized fertilization can adjust soil nutrient status, cut nutrient losses, and improve how efficiently crops take up nutrients (Guo *et al*., 2014). In particular, reducing nitrogen input has been shown to decrease nitrogen losses without compromising yield (Min *et al*., 2012). However, both studies were conducted under greenhouse conditions and did not consider the combined use of fertilization with soil conditioners. Our study differs by evaluating optimized fertilization together with a fulvic-acid-based conditioner in open-field tomato production on low-fertility soil in the Beijing suburbs, with two-year field data to capture interannual variation. However, fruit quality depends on many factors, especially fertilization regimes and growing conditions. Pre-harvest factors such as temperature, light, and water availability are particularly critical in shaping fruit quality and its seasonal variation (Fanourakis *et al*., 2025; Li *et al*., 2025). On top of that, applying too much fertilizer in tomato production raises the risk of nitrate leaching. Under these conditions, improving fertilization strategies to achieve a balance between yield, quality, and environmental sustainability is essential.

Compared with traditional solid organic fertilizers, organic water-soluble fertilizers provide nutrients in more readily available forms for crop uptake and can be applied efficiently through fertigation systems, combining the advantages of organic and chemical fertilizers (Shi *et al*., 2022). Owing to these advantages, organic water-soluble fertilizers have been shown to improve crop quality and soil conditions (Liu *et al*., 2024). These substances are able to raise the amount of organic matter added to the soil, improve soil aggregation and nutrient retention, and promote the transformation and availability of nitrogen, phosphorus, and potassium in the soil (Liu *et al*., 2025).

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These changes may enhance root nutrient uptake and subsequently affect tomato growth, yield formation, and fruit quality (Liu *et al.*, 2025). Song *et al*., (2025) reported that appropriate water–fertilizer irrigation could promote fruit enlargement and improve the fruit shape index. Wang et al. (2024) results showed that the treatment combining fulvic acid with a dual-bacterial inoculant performed best. While organic inputs can enhance lycopene content, antioxidant activity, and overall fruit quality (Stoleru *et al.*, 2020). Nitrogen levels also modulate how fertilization works. Research indicates that fulvic acid promotes growth more strongly when nitrogen supply is high (Wang *et al.*, 2025). Humic acid fertilizer also eased the conflict between high yield and good fruit quality. (Nie *et al.*, 2023).

Fulvic acid coming from natural humic materials, plays an important role in regulating the soil microenvironment (Yu *et al*., 2023). It contributes to processes such as pH buffering and aggregate formation, which in turn facilitate nitrogen transformation and improve root nitrogen uptake (Chen *et al*., 2023). It improves physiological growth, yield, and fruit quality and is widely used as a soil conditioner (Yazdani *et al.*, 2014). Lv *et al*., (2022) reported that fulvic acid application significantly increased soil nitrate nitrogen (NO_3^--N), ammonium nitrogen (NH_4^+-N), available phosphorus (AP), and available potassium (AK). Most existing research, however, has focused on soil processes and on crops such as cotton (Wang *et al.*, 2021), wheat (Liu *et al.*, 2021) and garlic (Yu *et al.*, 2023), whereas studies on open-field tomatoes remain limited.

To our knowledge, this is the first field-scale trial specifically evaluating the combination of optimized fertilization and a fulvic-acid-based soil conditioner in open-field tomato production in the Beijing suburbs. To address these concerns, we looked at how different fertilizer treatments affect soil properties, plant growth, yield, and fruit quality in open-field tomato production. The aim was to identify an optimized fertilization strategy that achieves a balance between high yield, improved quality, and efficient resource use.

Materials and methods

Study area: The experiment was set up at the Soil Improvement Experimental Base in Heishansi Village, Xiwengzhuang Town, Miyun District, Beijing (116°51′15″ E, 40°28′29″ N). This area has a temperate continental monsoon climate. Annual mean temperature hits 10.8°C, with 3813.4°C of accumulated heat when daily temperatures exceed 10°C, and average yearly rainfall over the long term is 430.4 mm. The site lies in a semi-mountainous, low-hill area that is fairly flat. The soil is loam. The initial soil physicochemical properties were as follows: pH 7.42, electrical conductivity (EC) 213 μS·cm^{-1}, OM 7.58 g·kg^{-1}, total nitrogen (TN) 0.51 g·kg^{-1}, AP 10.82 mg·kg^{-1}, and AK 130.20 mg·kg^{-1}. Figure 1 shows the location of the experimental site.

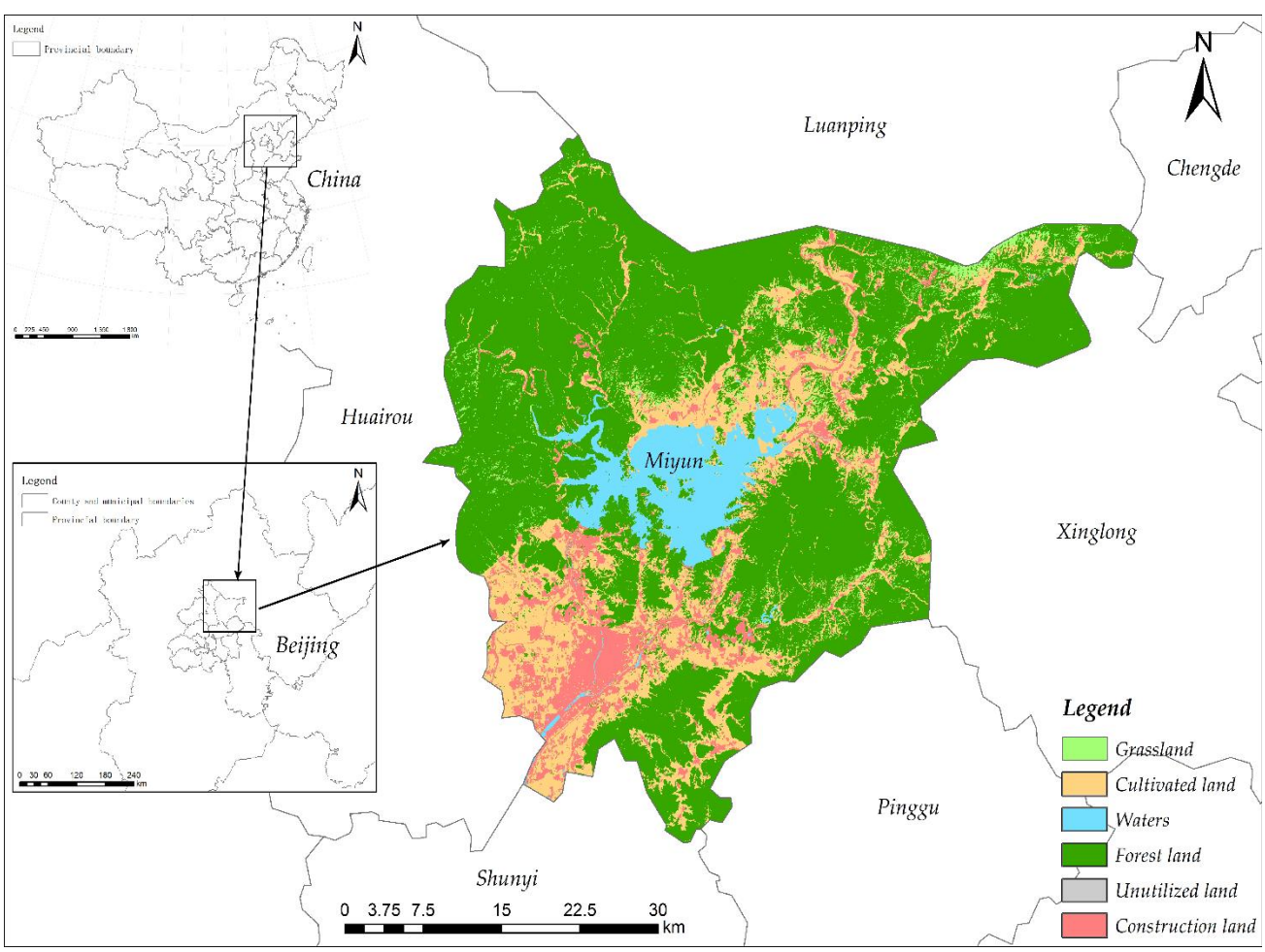


Fig. 1. Map of the experimental area.

Experimental materials: The basal fertilizers included sheep manure (total nutrients ≥ 4%, OM ≥ 30%, moisture ≤ 30%; N:P_2O_5:K_2O = 2:1:1), compound fertilizer (total nutrients ≥ 45%; N:P_2O_5: K_2O = 15:15:15), urea (total nutrients ≥ 46%), and monoammonium phosphate (MAP; total nutrients ≥ 55%; N:P_2O_5: K_2O = 11:44:0).

The water-soluble fertilizers included potassium dihydrogen phosphate (total nutrients ≥ 99%; N:P_2O_5: K_2O = 0:52:34); water-soluble macronutrient fertilizer A (total nutrients ≥ 50.0%; N:P_2O_5: K_2O = 30:10:10; Mg ≥ 10%); and water-soluble macronutrient fertilizer B (total nutrients ≥ 55.0%; N:P_2O_5: K_2O = 16:5:35), containing trace elements (Zn + B + Fe ≥ 0.15%) and supplemented with inositol (≥ 1.0%).

A humic acid–containing water-soluble fertilizer was also used (humic acid ≥ 30 g·L^{-1}; total N + P_2O_5 + K_2O ≥ 200 g·L^{-1}, including N ≥ 100 g·L^{-1}, P_2O_5 ≥ 40 g·L^{-1}, and K_2O ≥ 60 g·L^{-1}).

The soil conditioner was made mainly of fulvic acid, contained fulvic acid ≥ 50%, and K_2O ≥ 12%, with a pH range of 8–12.

Experimental design: The field trials took place between May and September in both 2024 and 2025. The tomato cultivar used was "Weidi No. 7B", with one cropping cycle per year under an integrated water–fertilizer management system. Four treatments were established: T1 (no fertilizer), T2 (conventional fertilization), T3 (optimized fertilization), and T4 (optimized fertilization combined with a soil conditioner). A randomized complete block design was adopted, with three replicates per treatment, providing sufficient statistical power to detect treatment differences. Each plot had an area of 58.8 m^2, and groundwater supplied the irrigation. Organic water-soluble fertilizers were applied through fertigation. Two drip tapes per ridge were installed, paced 30 cm apart. Each drip irrigation pipe had a diameter of 16 mm and a length of 7 m. Nozzles were arranged every 30 centimeters, with a rated flow rate of 2.0 L·h^{-1}. Tomatoes were planted at 30 cm row spacing and 50 cm plant spacing. Each ridge was 1.3-1.5 m wide and 7 m long. Guard rows of 1.5 m and 2.8 m were established, and a 1 m alley was kept between replications. Two rows were planted per ridge, giving a density of 30,612 plants ha^{-1}. A total of 180 plants grew in every plot.

Organic water-soluble fertilizers were adjusted through the fertigation system according to treatment requirements. Before transplanting, sheep manure and the basal portion of chemical fertilizers (Table 1) were spread evenly over the soil surface, then plowed in (20-30 cm), leveled, and ridged. Topdressing was applied once at each of the seedling, flowering, and fruiting stages. The total irrigation per plot over the growing season was 9 m^3. Nutrients supplied from sheep manure were not counted in stage-specific nutrient calculations, because manure was applied uniformly across all treatments as a background input and released nutrients slowly. Hence, stage-specific nutrient assessments focused mainly on chemical and functional fertilizer. Detailed fertilization schemes and total application rates for each treatment are presented in Table 1.

Observations and measurements

Measurement of soil nutrient indicators: After the harvest finished, soil sampling was done in every plot. Sampling was conducted after the final irrigation event. A soil auger of 3.5 cm was used, avoiding fertilizer application points. Representative points were selected along the diagonals of each plot using a five-point sampling approach. Soil sampling covered 3 depth intervals: 0-20 cm, 20-40 cm, and 40-60 cm. For each depth, soils from the 5 sampling points were mixed thoroughly, and subsamples were prepared using the quartering method. Samples were then packaged, labeled, and stored for physicochemical analyses (Bao, 2000; Lu, 2000).

The hydrometer method, in line with standard protocols, was employed to measure how soil particles were distributed by size (Bao, 2000). The soil was composed of 43.2% sand, 38.7% silt, and 18.1% clay. According to USDA textural classes, this soil was a loam (Bao, 2000; Soil Survey Staff *et al.*, 2017).

Soil pH was determined by the potentiometric method, employing CO_2-free distilled water and a 1:2.5 soil-to-water mixture (Bao, 2000). EC was determined using the electrode method following standard procedures described by Bao (2000). The Kjeldahl technique served to determine TN (Bao, 2000; Lu, 2000). OM concentration was analyzed by the potassium dichromate oxidation–titration method (Bao, 2000). AP was measured using the molybdenum–antimony anti-spectrophotometric method (Bao, 2000), AK measurement employed NH_4OAc extraction and subsequent flame photometry (Bao, 2000; Lu, 2000). The indophenol blue colorimetric method served to quantify NH_4^+-N, while ultraviolet spectrophotometry was used for NO_3^--N (Bao, 2000; Lu, 2000).

Determination of nutrient parameters in tomato plants: Each plot provided 5 typical plants at harvest. These plants had average growth and were free from visible pests or diseases. They were chosen randomly from the plot's inner area. (excluding guard rows). Roots, stems, and leaves were separated and collected for analysis. Plant tissues were digested using an H_2SO_4-H_2O_2 mixture to prepare analytical solutions (Bao, 2000), . TN was determined by the Kjeldahl method (Bao, 2000), total phosphorus (TP) by the molybdenum-antimony anti-spectrophotometric method (Bao, 2000), and total potassium (TK) by flame photometry (Bao, 2000).

Determination of growth, yield, and quality parameters of tomato: Plant height (PH) was defined as the straight-line distance from the soil surface up to the apical growing point. Stem diameter (SD) was measured at 1 cm above the cotyledon node using a digital vernier caliper. A vernier caliper gave measurements of fruit length and diameter. The fruit shape index then came from dividing average fruit length by average fruit diameter (Gonzalo *et al*., 2008). Total yield was calculated based on cumulative harvests per plot and expressed on an area basis (Yang *et al*., 2025).

For fruit quality assessment, a random set of 15 fruits came from the five typical plants per plot. These were then mixed to make one composite sample. All fruits were harvested at commercial maturity with uniform external coloration. The 2,6-dichloroindophenol titration procedure gave VC content (Anon., 2005). TA came from NaOH titration (Anon., 2005). A digital refractometer provided SSC values (Anon., 2005). SAR was calculated as SSC divided by TA. For SPAD measurements, from the top, the third fully expanded and functional leaf was chosen. Measurements were obtained using a SPAD-502

chlorophyll meter, with three readings per leaf averaged for analysis (Anon.,1989).

The calculation formulas for fertilizer use efficiency (FUE), crop nutrient uptake (CNU), agronomic efficiency of fertilizer (AE), and partial factor productivity of fertilizer (PFP) were applied as described in He *et al*., (2025).

$$FUE=\frac{CNU-CNU_0}{FAR}\cdot 100\% \quad (1)$$

$$CNU=ODW\ (g\cdot plant^{-1})\cdot NC\ (g\cdot kg^{-1}) \quad (2)$$

$$AE\left(kg\cdot kg^{-1}\right)=\frac{Y-Y_0}{FAR} \quad (3)$$

$$PFP\left(kg\cdot kg^{-1}\right)=\frac{Y}{FAR} \quad (4)$$

Note: FUE: fertilizer use efficiency; CNU: crop nutrient uptake under fertilized conditions; CNU_0: crop nutrient uptake in the unfertilized treatment; FAR: fertilizer application rate; ODW: organ dry weight; NC: nutrient concentration; AE: agronomic efficiency of fertilizer; Y: yield; Y_0: yield in the unfertilized treatment; PFP: partial factor productivity of fertilizer.

Statistical analysis

Microsoft Excel 2019 was used for data processing. A one-way analysis of variance (ANOVA) was performed with SPSS 22.0. Treatment means were then compared using Tukey's HSD test at the 0.05 significance level. Graphs were generated using Origin 2024, while some figures were generated using the ggplot2 package in R (version 4.5.2, R Foundation for Statistical Computing, Vienna, Austria) (He *et al*., 2025).

Results

Effects of different fertilization treatments on soil physicochemical properties: Table 2 presents, soil pH and EC under the different fertilization treatments showed variation across soil layers, and significant interannual variation was observed between the two study years. Soil pH fluctuated slightly with increasing depth, whereas EC values were generally higher under the T2 treatment. For the topsoil (0-20 cm), T2 gave a higher pH than the other treatments did in 2024 ($p<0.05$). In 2025, however, no significant differences were detected among treatments, with pH values ranging from 7.30 to 7.66. Across all soil layers, EC was highest under T2, whereas EC was significantly reduced under T4. Relative to T2, T4 decreased EC in the 0-20 cm layer by 25.87% and 17.02% in 2024 and 2025, respectively. For the subsurface layer (20-40 cm), EC was decreased by 25.57% and 11.43%, while in the 40-60 cm layer, reductions reached 31.84% and 30.25%. For each soil layer, pH was similar regardless of treatment in 2025.

Regarding soil nutrient distribution, every measured nutrient declined as soil depth increased. Among the 4 treatments, T4 did the most to improve soil fertility. For AP, in the 0-20 cm layer, AP content under T4 was significantly above the levels in all other treatments, and this held true for both 2024 and 2025 ($p < 0.05$). Compared with T2, T4 increased AP by 4.72% and 6.33% in 2024 and 2025, respectively. These differences were mainly concentrated in the surface layer (0-20 cm); however, a significant difference also occurred in the 20-40 cm layer in 2025. For AK, T4 showed a clear advantage across all soil layers. For the topsoil (0-20 cm), AK under T4 was 26.44% and 25.27% higher than that under T2 in 2024 and 2025, respectively. In addition, in 2025, AK under T4 was significantly higher ($p<0.05$) than that under T2 at 20-40 cm and 40-60 cm deep with increases of 27.06% and 14.09%, respectively. The trends in OM and TN differed slightly, but T4 showed the best performance overall ($p<0.05$). For TN, the content (0-20 cm) under T4 was increased by 19.30% and 20.00% compared with T2 in 2024 and 2025, respectively. At 20-40 cm and 40-60 cm deep, TN under T4 was increased by 10.91%-17.54% and 23.81%-27.27%, respectively. For OM, the concentration (0-20 cm) under T4 increased by 33.40% and 33.43% compared with T2 in 2024 and 2025, respectively. In addition, OM concentration under T4 was significantly higher than that under the other treatments ($p < 0.05$), except in the 20-40 cm layer in 2024. (Bar charts summarizing the key trends of soil nutrients across treatments and soil depths are provided in Appendix A).

Under the unified irrigation regime, T4 significantly increased soil AP, AK, TN, and OM. These improvements were more pronounced (0-40 cm). Optimized fertilization supplemented with a soil conditioner is effective for enhancing soil nutrient status.

Effects of different fertilization treatments on tomato growth and nutrient uptake

Effects of different fertilization treatments on tomato growth: As shown in Figure 2, PH, SD, and SPAD values increased across growth stages under all treatments in both 2024 and 2025, with T4 generally maintaining higher levels during key phenological stages. At the seedling stage (1 d after transplanting), none of the three indicators showed clear differences across treatments. From the flowering stage (40 d after transplanting), T4 raised pH more than the other treatments did ($p<0.05$). Relative to T2, the increase came to 14.31% in 2024 and 13.66% in 2025. Over the same period, SD was increased by 13.62% and 15.70%, and SPAD value was increased by 8.37% and 5.32%, respectively. At the fruit expansion stage (80 d after transplanting), the pH under T4 kept growing and stayed clearly above the other treatments ($p<0.05$), with increases of 18.56% (2024) and 17.68% (2025) relative to T2. For SD, T4 was significantly higher than T1 and T2 in 2024, and SD was increased by 8.52% and 11.01% compared with T2 in 2024 and 2025, respectively. SPAD values were highest under T4 in 2024 ($p<0.05$), increasing by 15.80% and 29.82% relative to T2 in 2024 and 2025, respectively. At the maturity stage (120 d after transplanting), PH, SD, and SPAD values under T4 remained higher. In 2024, they were increased by 3.28%, 8.55%, and 18.80% compared with T2, respectively; in 2025, the corresponding increases were 9.07%, 11.52%, and 24.20%.

T4 clearly boosted tomato growth. Across growth stages, its PH, SD, and SPAD values were always higher. The combination of optimized fertilization and a soil conditioner kept plants vigorous with raised chlorophyll levels. In turn, that resulted in higher yield and better fruit quality.

Appendix A. Supplementary data

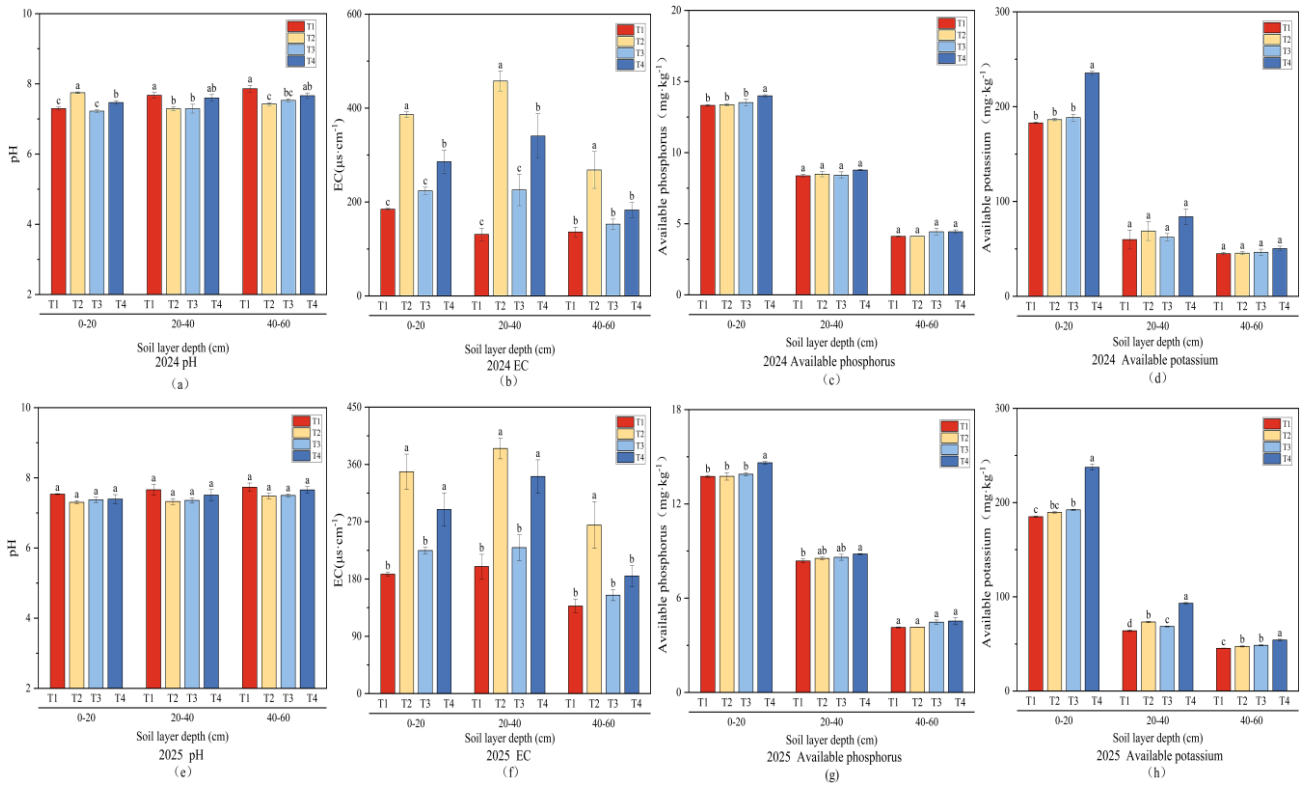


Fig. S1. The effects of different fertilization treatments on pH, EC, available phosphorus, and available potassium in 2024 and 2025. (a, b, c, d) pH, EC, AP, AK of 2024; (e, f, g, h) pH, EC, AP, AK of 2025.
Note: Different letters differ significantly among treatments (p<0.05). Bars sharing a letter show no such difference (p>0.05). Error bars represent standard errors (SE) of three replicates.

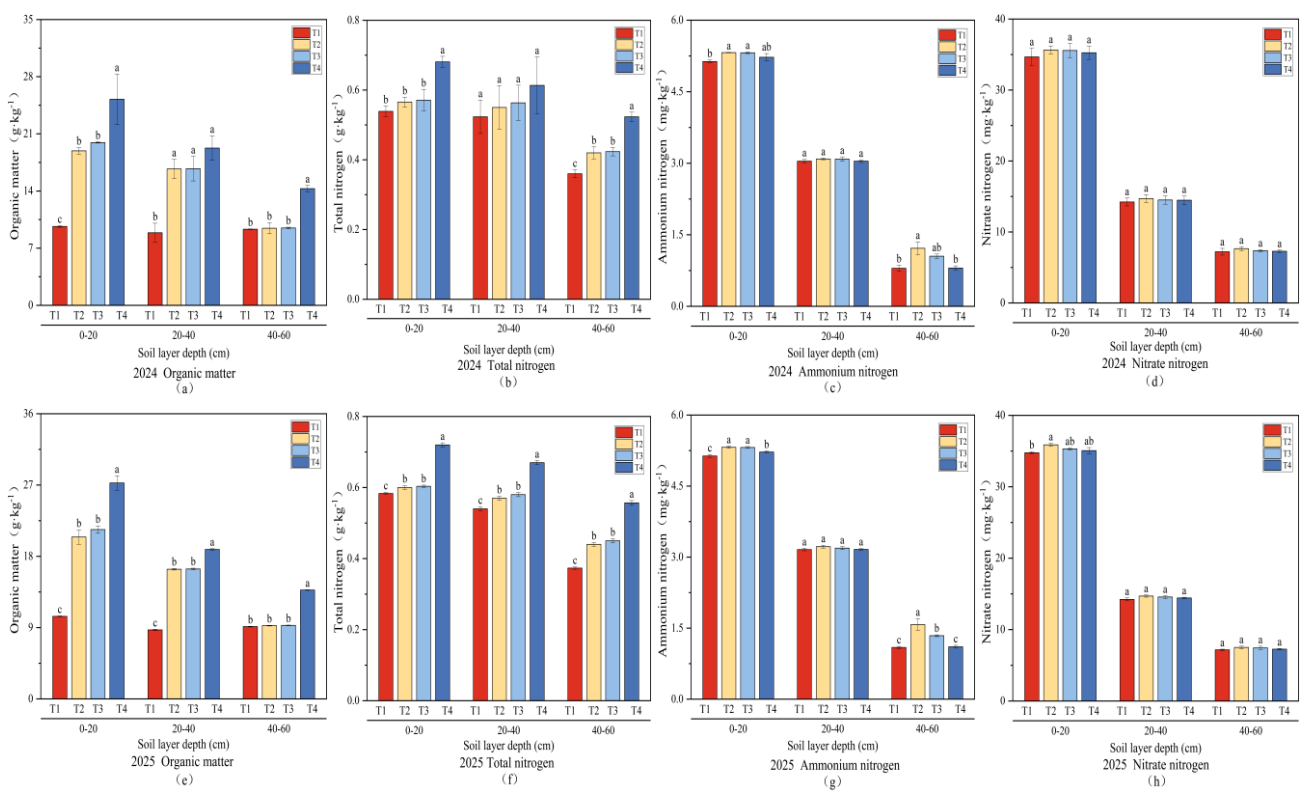


Fig. S2. The effects of different fertilization treatments on organic matter, total nitrogen, ammonium nitrogen, and nitrate nitrogen in 2024 and 2025. (a, b, c, d) OM, TN, NH_4^+-N, NO_3^--N of 2024; (e, f, g, h) OM, TN, NH_4^+-N, NO_3^--N of 2025.
Note: Different letters differ significantly among treatments (p<0.05). Bars sharing a letter show no such difference (p>0.05). Error bars represent standard errors (SE) of three replicates.

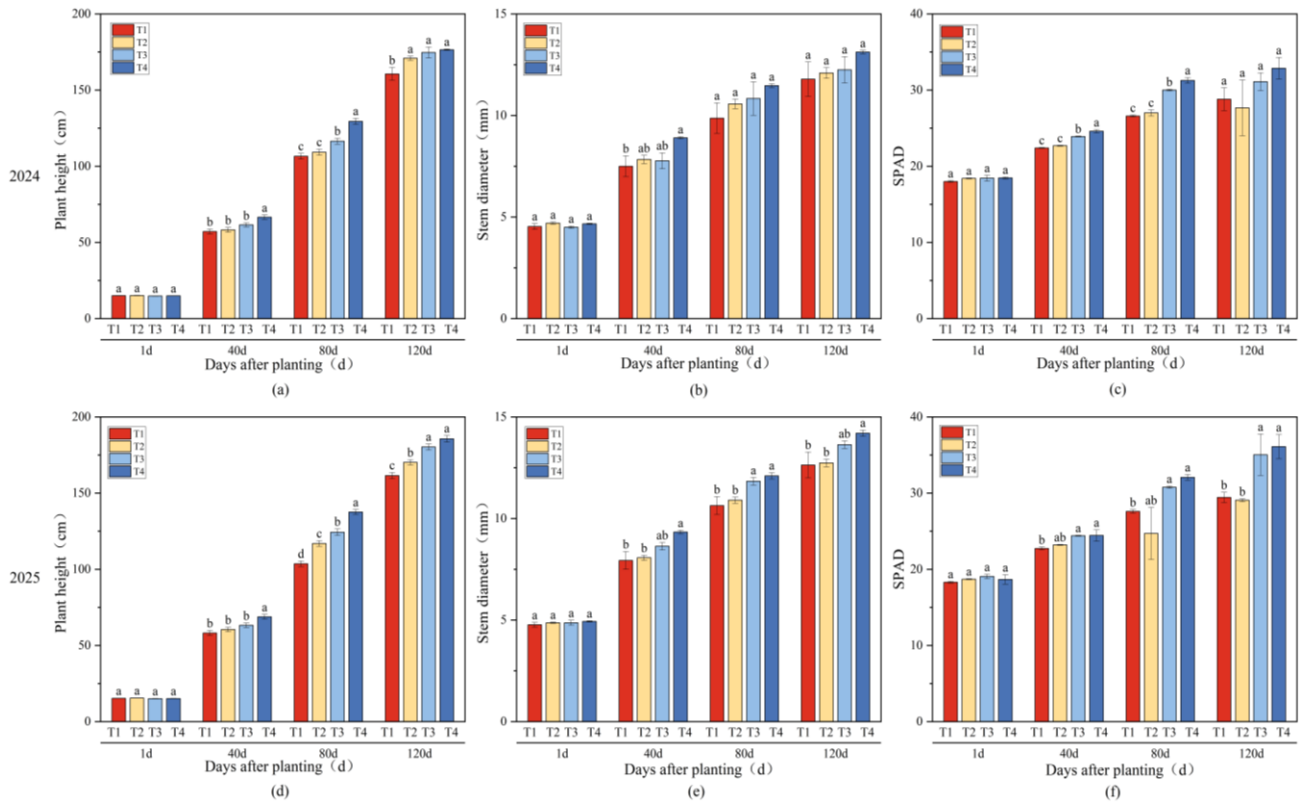


Fig. 2. The effects of different fertilization treatments on plant height (PH), stem diameter (SD), and SPAD value in 2024 and 2025. (a, b, c) PH, SD, and SPAD across the growth stages of 2024; (d, e, f) PH, SD, and SPAD across the growth stages of 2025

Note: Different letters differ significantly among treatments (p<0.05). Bars sharing a letter show no such difference (p>0.05). Error bars represent standard errors (SE) of three replicates.

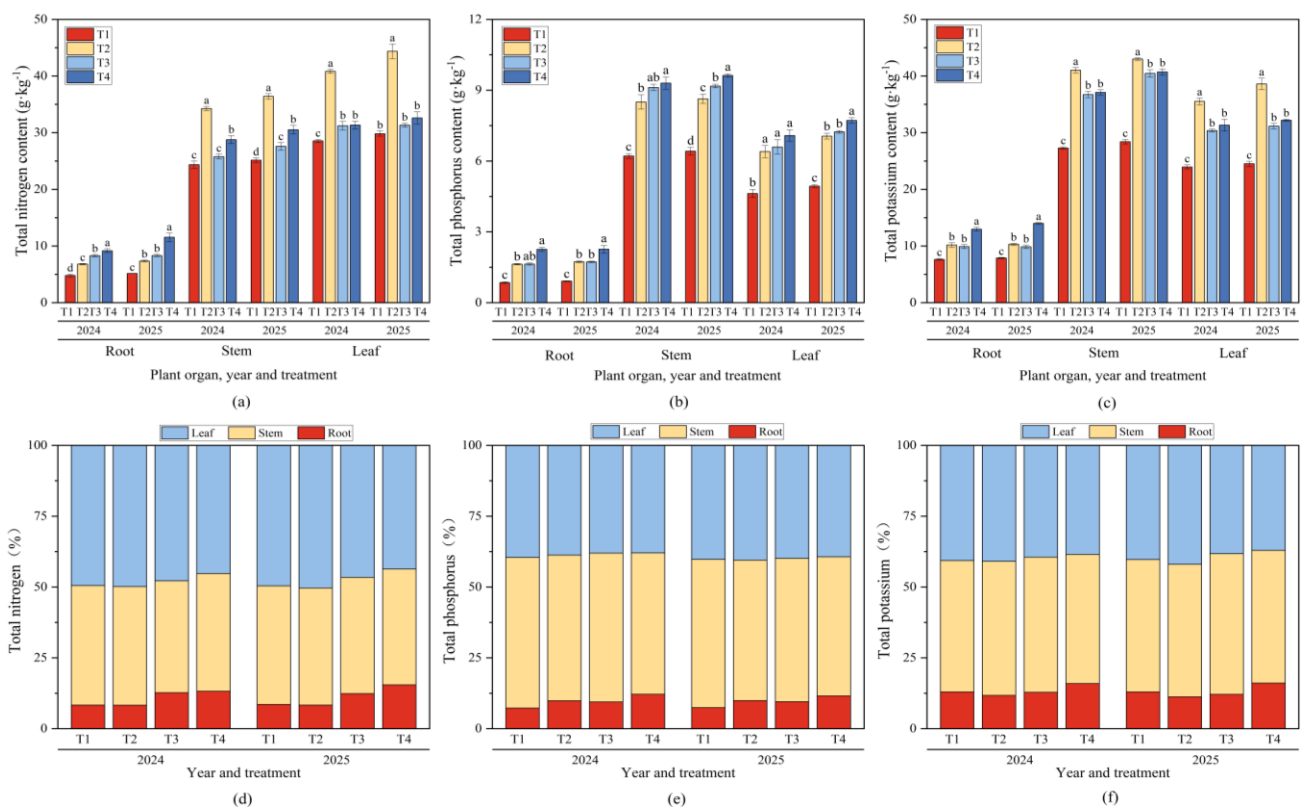


Fig. 3. The effects of different fertilization treatments on nutrient uptake in roots, stems, and leaves in 2024 and 2025. (a, b, c) For the years 2024 and 2025, the amounts of TN, TP, and TK in roots, stems, and leaves across the different treatments; (d, e, f) Roots, stems, leaves: TN, TP, TK distribution by treatment, 2024-2025.

Note: Different letters differ significantly among treatments (p<0.05). Bars sharing a letter show no such difference (p>0.05). Error bars represent standard errors (SE) of three replicates.

Table 1. Experimental fertilization plan.

Treatment	Topdressing					Basal Fertilization				Nutrient Content		
	A ($kg \cdot ha^{-1}$)	B ($kg \cdot ha^{-1}$)	potassium dihydrogen phosphate ($kg \cdot ha^{-1}$)	Humic acid–containing water-soluble fertilizer ($L \cdot ha^{-1}$)	Soil conditioner ($kg \cdot ha^{-1}$)	Sheep manure ($t \cdot ha^{-1}$)	Conventional compound fertilizer ($kg \cdot ha^{-1}$)	Monoammonium phosphate ($kg \cdot ha^{-1}$)	Urea ($kg \cdot ha^{-1}$)	N ($kg \cdot ha^{-1}$)	P_2O_5 ($kg \cdot ha^{-1}$)	K_2O ($kg \cdot ha^{-1}$)
T1 no fertilization	0	0	0	0	0	0.0	0	0	0	0	0	0
T2 conventional fertilization	33.6	433.9	64.3	0	0	15.0	750.0	0	0	192.0	171.0	289.6
T3 optimized fertilization	116.6	456.4	60.6	0	0	15.0	320.0	115.9	24.5	180.0	165.0	240.0
T4 optimized fertilization with a soil conditioner	116.6	456.4	60.6	75.0	45.0	15.0	320.0	115.9	24.5	187.5	168.0	249.9

Note: A: Water-soluble macronutrient fertilizer A: ($N:P_2O_5:K_2O = 30:10:10$); B: Water-soluble macronutrient fertilizer B ($N:P_2O_5:K_2O = 16:5:35$)

Table 2. The impact of different fertilization treatments on soil physicochemical properties in 2024 and 2025.

Year	Treatment	Soil layer depth	pH	EC ($\mu S \cdot cm^{-1}$)	Organic matter ($g \cdot kg^{-1}$)	Available phosphorus ($mg \cdot kg^{-1}$)	Total nitrogen ($g \cdot kg^{-1}$)	Available potassium ($mg \cdot kg^{-1}$)	Ammonium nitrogen ($mg \cdot kg^{-1}$)	Nitrate nitrogen ($mg \cdot kg^{-1}$)
2024	T1	0-20 cm	7.30 ± 0.05c	184.73 ± 1.74c	9.66 ± 0.09c	13.32 ± 0.06b	0.54 ± 0.02b	182.83 ± 0.66b	5.13 ± 0.03b	34.67 ± 1.21a
	T2		7.75 ± 0.02a	385.80 ± 6.07a	18.92 ± 0.40b	13.36 ± 0.09b	0.57 ± 0.01b	186.30 ± 1.19b	5.32 ± 0.01a	35.65 ± 0.58a
	T3		7.22 ± 0.04c	223.93 ± 7.43c	19.94 ± 0.07b	13.52 ± 0.23b	0.57 ± 0.03b	188.43 ± 3.67b	5.32 ± 0.02a	35.57 ± 1.00a
	T4		7.47 ± 0.05b	286.00 ± 24.27b	25.24 ± 3.08a	13.99 ± 0.07a	0.68 ± 0.02a	235.55 ± 1.83a	5.22 ± 0.08ab	35.26 ± 0.93a
	T1	20-40 cm	7.67 ± 0.08a	131.20 ± 13.24c	8.89 ± 1.16b	8.37 ± 0.11a	0.52 ± 0.05a	59.80 ± 10.00a	3.04 ± 0.04a	14.23 ± 0.55a
	T2		7.29 ± 0.05b	457.57 ± 21.07a	16.70 ± 1.19a	8.49 ± 0.18a	0.55 ± 0.06a	68.78 ± 9.92a	3.09 ± 0.02a	14.71 ± 0.56a
	T3		7.29 ± 0.13b	225.60 ± 33.42c	16.73 ± 1.51a	8.41 ± 0.24a	0.56 ± 0.05a	62.30 ± 3.84a	3.09 ± 0.05a	14.52 ± 0.59a
	T4		7.60 ± 0.10ab	340.57 ± 47.61b	19.26 ± 1.50a	8.77 ± 0.04a	0.61 ± 0.08a	83.87 ± 8.30a	3.04 ± 0.03a	14.48 ± 0.61a
	T1	40-60 cm	7.86 ± 0.10a	136.33 ± 10.31b	9.32 ± 0.04b	4.11 ± 0.03a	0.36 ± 0.01c	45.00 ± 1.29a	0.80 ± 0.06b	7.22 ± 0.48a
	T2		7.43 ± 0.04c	268.33 ± 39.31a	9.44 ± 0.68b	4.12 ± 0.01a	0.42 ± 0.02b	45.43 ± 1.64a	1.22 ± 0.13a	7.66 ± 0.28a
	T3		7.53 ± 0.04bc	152.97 ± 10.60b	9.47 ± 0.10b	4.43 ± 0.24a	0.42 ± 0.01b	46.45 ± 3.27a	1.05 ± 0.05ab	7.38 ± 0.14a
	T4		7.66 ± 0.08ab	182.90 ± 16.11b	14.29 ± 0.39a	4.44 ± 0.14a	0.52 ± 0.01a	50.33 ± 2.55a	0.80 ± 0.05b	7.29 ± 0.16a
2025	T1	0-20 cm	7.54 ± 0.01a	187.53 ± 3.28b	10.43 ± 0.05c	13.75 ± 0.06b	0.58 ± 0.00c	185.08 ± 0.77c	5.14 ± 0.03c	34.77 ± 0.17b
	T2		7.30 ± 0.05a	348.60 ± 27.76a	20.43 ± 0.91b	13.75 ± 0.24b	0.60 ± 0.01b	189.59 ± 0.81bc	5.32 ± 0.02a	35.87 ± 0.22a
	T3		7.37 ± 0.07a	224.77 ± 4.82b	21.38 ± 0.47b	13.89 ± 0.09b	0.60 ± 0.00b	192.30 ± 0.55b	5.32 ± 0.02a	35.30 ± 0.14ab
	T4		7.39 ± 0.13a	289.27 ± 26.22a	27.26 ± 0.91a	14.62 ± 0.09a	0.72 ± 0.01a	237.49 ± 3.17a	5.22 ± 0.02b	35.07 ± 0.42ab
	T1	20-40 cm	7.66 ± 0.16a	199.67 ± 19.16b	8.71 ± 0.06c	8.37 ± 0.12b	0.54 ± 0.01c	63.96 ± 0.88d	3.16 ± 0.06a	14.23 ± 0.21a
	T2		7.33 ± 0.08a	385.10 ± 16.35a	16.37 ± 0.10b	8.53 ± 0.09ab	0.57 ± 0.01b	73.31 ± 0.68b	3.22 ± 0.03a	14.70 ± 0.15a
	T3		7.36 ± 0.08a	229.27 ± 20.09b	16.40 ± 0.10b	8.60 ± 0.19ab	0.58 ± 0.01b	68.52 ± 0.47c	3.19 ± 0.03a	14.57 ± 0.18a
	T4		7.51 ± 0.16a	341.10 ± 26.22a	18.87 ± 0.11a	8.81 ± 0.04a	0.67 ± 0.01a	93.15 ± 0.80a	3.16 ± 0.02a	14.44 ± 0.09a
	T1	40-60 cm	7.73 ± 0.12a	137.57 ± 10.67b	9.13 ± 0.05b	4.14 ± 0.03a	0.37 ± 0.00c	45.42 ± 0.27c	1.09 ± 0.02c	7.17 ± 0.08a
	T2		7.48 ± 0.08a	264.83 ± 36.81a	9.25 ± 0.05b	4.16 ± 0.01a	0.44 ± 0.01b	47.42 ± 0.68b	1.58 ± 0.12a	7.50 ± 0.20a
	T3		7.50 ± 0.04a	154.60 ± 8.57b	9.28 ± 0.05b	4.48 ± 0.14a	0.45 ± 0.01b	48.52 ± 0.50b	1.34 ± 0.02b	7.43 ± 0.23a
	T4		7.66 ± 0.10a	184.73 ± 16.31b	13.74 ± 0.05a	4.54 ± 0.22a	0.56 ± 0.01a	54.10 ± 0.89a	1.11 ± 0.03c	7.27 ± 0.09a

Note: Different lowercase letters mark significant treatment differences ($p<0.05$). The same letter means no such difference

Effects of different fertilization treatments on nutrient uptake and allocation in tomato plants: Figure 3 shows how fertilizer treatments changed N, P, and K contents and their distribution across roots, stems, and leaves. Overall, TN under all treatments followed the order leaf > stem > root. The T2 treatment resulted in the highest TN contents in stems and leaves (p<0.05), whereas, T4 significantly increased root TN, with increases of 34.84% and 57.39% relative to T2 in 2024 and 2025, respectively. Across treatments, TP and TK generally followed the order stem > leaf > root. T4 showed a comprehensive advantage in phosphorus uptake. In 2025, TP in roots, stems, and leaves under T4 clearly outperformed the other treatments. In 2024, TP under T4 increased by 38.93%, 9.37%, and 10.68% relative to T2 in roots, stems, and leaves, respectively; in 2025, the corresponding increases were 31.27%, 11.47%, and 9.46%. For potassium, T2 resulted in higher TK contents in stems and leaves, whereas under T4 potassium accumulation in roots (p<0.05) was significantly increased with root TK increasing by 27.47% and 35.73% relative to T2 in 2024 and 2025, respectively.

As shown in Fig. 3(d-f), regarding different fertilization treatments, each treatment exerted some influence on nutrient allocation among plant organs. Overall, treatments with higher fertilization levels (T3 and T4) resulted in relatively higher nutrient allocation ratios in the roots, while the low fertilization treatment (T1) led to relatively higher allocation ratios in the leaves. What these results indicate: good fertilization management can make nutrient distribution more balanced across different plant organs.

T2 was mainly associated with higher TN and TK contents in stems and leaves, whereas T4 significantly increased TN, TP, and TK in roots, with particularly pronounced effects on root TN and TK accumulation. These results indicate that fertilization regimes differentially influence nutrient distribution among organs, and that T4 is conducive to optimizing nutrient allocation and strengthening root function.

Effects of different fertilization treatments on tomato yield: The responses of single fruit weight, fruit shape index (FSI), and yield to fertilization treatments showed similar patterns in 2024 and 2025. In 2024, single fruit weight showed no clear differences across treatments (Table 3). In 2025, T4 clearly outperformed T1 and T2 in single fruit weight (p<0.05), but did not differ significantly from T3. In both years, single fruit weight under T4 was increased by 14.63% (31.99 g) and 17.16% (35.02 g), respectively, compared with T2. However, across both years, FSI did not differ clearly by treatment. For yield, T4 consistently produced the highest yields in both years and clearly outperformed the other treatments (p<0.05), increasing by 25.18% (2352.11 kg·ha^{-1}) and 27.24% (2659.18 kg·ha^{-1}) relative to T2 in 2024 and 2025, respectively. In addition, yield under T4 in 2025 was 6.21% (726.33 kg·ha^{-1}) higher than that in 2024. In summary, under unified irrigation conditions, T4 significantly increased tomato yield and improved single fruit weight to some extent, with a progressively stronger yield-enhancing effect over time.

Effects of different fertilization treatments on tomato quality: Figure 4 showed that at commercial maturity, fertilization treatments produced similar trends in fruit quality indices in 2024 and 2025. In 2024, SSC showed no significant treatment differences. In 2025, SSC under T4 clearly outperformed T1 and T2 (p<0.05), increasing by 17.39% (1.07 °Brix) relative to T2; moreover, SSC under T4 in 2025 was 9.09% (0.60 °Brix) higher than in 2024. The two-year average increase of 9.99% (0.62 °Brix) in SSC (relative to T2) was driven primarily by the 2025 data. TA showed no significant differences among treatments in either year. The SAR was highest under T4 in 2024, being significantly higher than under T1 and T2 (p<0.05) and increasing by 5.62% (0.45) relative to T2. In 2025, SAR did not differ significantly among treatments; nevertheless, SAR under T4 in 2025 was 4.93% (0.41) higher than in 2024. VC content under T4 clearly outperformed the other treatments in both years (p<0.05), increasing by 28.82% (4.47 mg·100g^{-1}) and 24.28% (4.30 mg·100g^{-1}) relative to T2 in 2024 and 2025, respectively. VC content under T4 was increased by 10.33% (2.06 mg·100g^{-1}) in 2025 compared with 2024.

T4 significantly improved SAR and VC content. These improvements were consistent across observations and may contribute to better nutritional value and taste.

Effects of different fertilization treatments on fertilizer use efficiency: Fertilization treatments significantly influenced nitrogen-, phosphorus-, and potassium-related efficiency indices (Fig. 5). Taken together, fertilizer use efficiency followed the order T4 > T3 > T2, with T4 showing significantly higher values than the other treatments for multiple indices (p<0.05). This pattern was consistent across both experimental years.

For PFP, PFPN, PFPP, and PFPK were all significantly higher under T4 (p<0.05). Compared with T2, PFPN under T4 was increased by 43.95% and 46.33% in 2024 and 2025, respectively; PFPP was increased by 41.11% and 43.44%; and PFPK was increased by 58.81% and 61.45%, respectively. For FUE, T4 also showed superior performance. Relative to T2, NUE under T4 increased by 7.24% and 1.80% in 2024 and 2025, respectively; PUE rose 1.20 times and 1.21 times; and KUE increased by 60.21% and 54.26%, respectively. With respect to AE, improvements under T4 were more pronounced (p<0.05). Compared with T2, for T4, AEN rose 1.48 times in 2024 and 1.52 times in 2025, respectively; AEP rose 1.43 times and 1.47 times, AEK rose 1.74 times and 1.78 times, respectively.

Table 3. The effects of different fertilization treatments on single fruit weight, fruit shape index, and yield in 2024 and 2025.

Year	Treatment	Single fruit weight (g)	Fruit shape index	Yield (kg·ha^{-1})
2024	T1	212.38 ± 10.94a	0.79 ± 0.01a	7310.32 ± 166.42c
	T2	218.73 ± 2.50a	0.81 ± 0.04a	9342.65 ± 214.41b
	T3	243.71 ± 8.25a	0.84 ± 0.03a	10331.02 ± 383.03b
	T4	250.72 ± 21.49a	0.83 ± 0.02a	11694.76 ± 384.90a
2025	T1	206.91 ± 5.77b	0.84 ± 0.05a	7535.71 ± 95.49d
	T2	204.03 ± 3.81b	0.88 ± 0.04a	9761.91 ± 25.20c
	T3	223.92 ± 9.06ab	1.00 ± 0.10a	10611.63 ± 39.46b
	T4	239.05± 8.58a	0.98 ± 0.08a	12421.09 ± 178.09a

Note: Different lowercase letters mark a treatment difference at p<0.05. Sharing the same letter means p>0.05 (no significant difference)

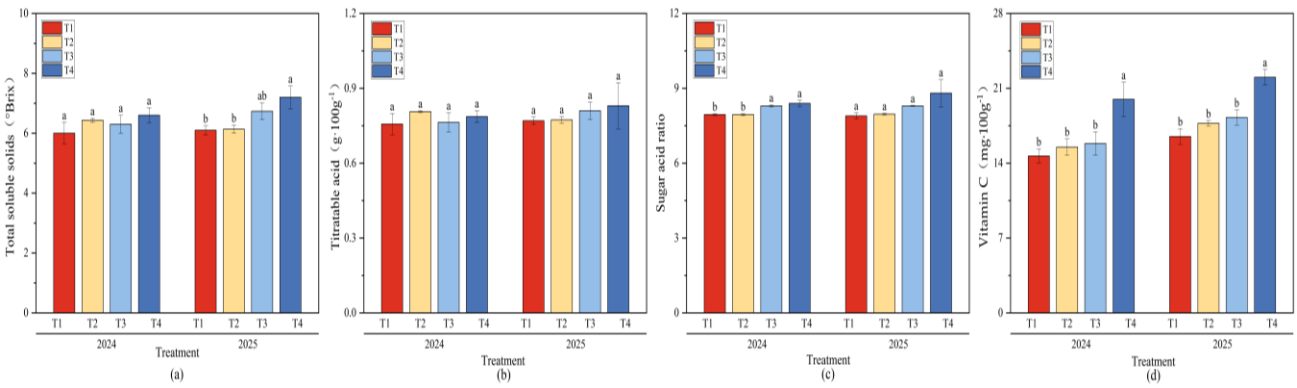


Fig. 4. The effects of different fertilization treatments on soluble solids (SSC), titratable acid (TA), sugar acid ratio (SAR), and vitamin C (Vc) content in 2024 and 2025. (a, b, c, d) SSC, TA, SAR, and VC in 2024 and 2025.
Note: Different letters differ significantly among treatments (p<0.05). Bars sharing a letter show no such difference (p>0.05). Error bars represent standard errors (SE) of three replicates.

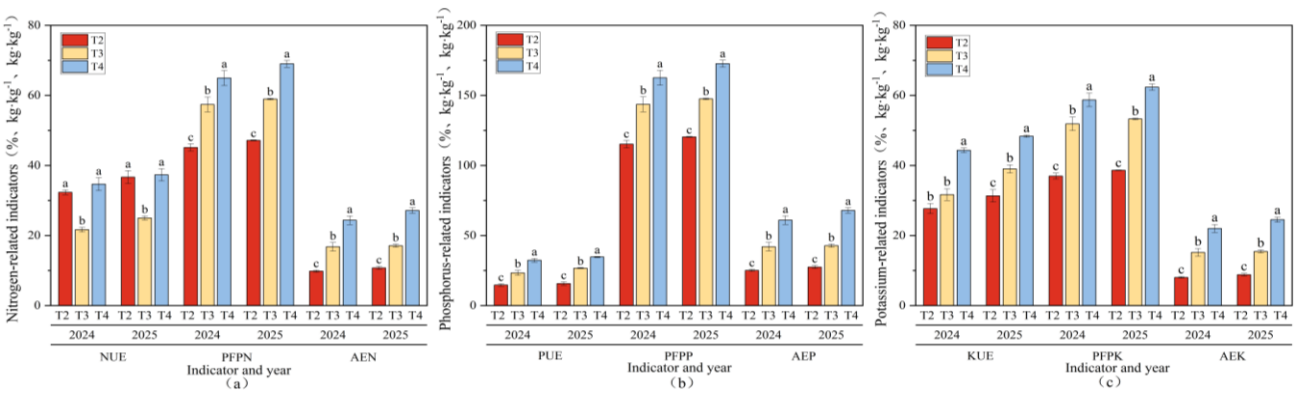


Fig. 5. Fertilizer use efficiency (FUE), partial factor productivity of fertilizer (PFP), and agronomic efficiency (AE) under different fertilization treatments in 2024 and 2025. (a) NUE, PFPN, and AEN in 2024 and 2025; (b) PUE, PFPP, and AEP; (c) KUE, PFPK, and AEK.
Note: Different letters differ significantly among treatments (p<0.05). Bars sharing a letter show no such difference (p>0.05). Error bars represent standard errors (SE) of three replicates.

Under unified irrigation conditions, T4 significantly improved PFP, FUE, and AE for nitrogen, phosphorus, and potassium, indicating that optimized fertilization combined with a soil conditioner represents an effective technical pathway for fertilizer reduction and efficiency enhancement in open-field tomato production.

Correlation Analysis

This study used Mantel tests to check correlations between soil, growth, quality, and nutrient variables versus yield and fertilizer efficiency variables (the two variable groups linked by lines in Figs. 6 and 7). Solid lines mean p<0.05, dashed lines mean p>0.05. Figure 6 showed that tomato yield and nitrogen, phosphorus, and potassium use efficiencies in 2024 were jointly influenced by soil physicochemical properties and plant growth indicators. Yield was significantly positively correlated with OM, AP, TN, AK, PH, SAR, VC, Root N, P, K, Stem P, K, and Leaf P, K, and negatively correlated with pH and EC. NUE was significantly positively correlated with EC, OM, AK, and PH, as well as Root N, P, K, Stem N, P, K, and Leaf N, P, and K. PUE and KUE were significantly positively correlated with OM, AP, TN, AK, PH, SAR, VC, Root N, P, K, Stem P, K, and Leaf P. Moreover, KUE exhibits a positive correlation with leaf Leaf K. OM was significantly positively correlated with AP, TN, AK, PH, SAR, VC, Root N, P, K, Stem P, K, and Leaf P and K. In contrast, soil pH showed a clear negative link with EC, OM, NH_4^+-N, Stem N, P, Kand the Leaf N, P, and K.

Tomato yield and nitrogen, phosphorus, and potassium use efficiencies in 2025 were jointly influenced by soil physicochemical properties and plant growth indicators (Fig. 7). Yield was significantly positively correlated with OM, AP, TN, AK, PH, SD, SPAD values, SSC, SAR, VC, Root N, P, K, Stem P, K, and Leaf P, and negatively correlated with pH and EC. NUE was significantly positively correlated with EC, OM, PH, VC, and Leaf N, P, and K. PUE and KUE were significantly positively correlated with OM, AP, TN, AK, PH, SD, SPAD values, SSC, VC, Root N, P, K, Stem P, K, and Leaf P; PUE was also positively correlated with SAR. KUE was also positively correlated with NH_4^+-N, and Leaf K. OM was significantly positively correlated with AP, TN, AK, PH, SD, SPAD, SSC, VC, Root N, P, K, Stem P, K, and Leaf P and K. EC was significantly positively correlated with NH_4^+-N, Root P, Stem N, K, and Leaf N, P, and K, whereas pH was significantly negatively correlated with EC, Stem N, and Leaf K. Significant positive correlations were also observed among Root N, P, K, Stem N, P, K, and Leaf N, P, and K.

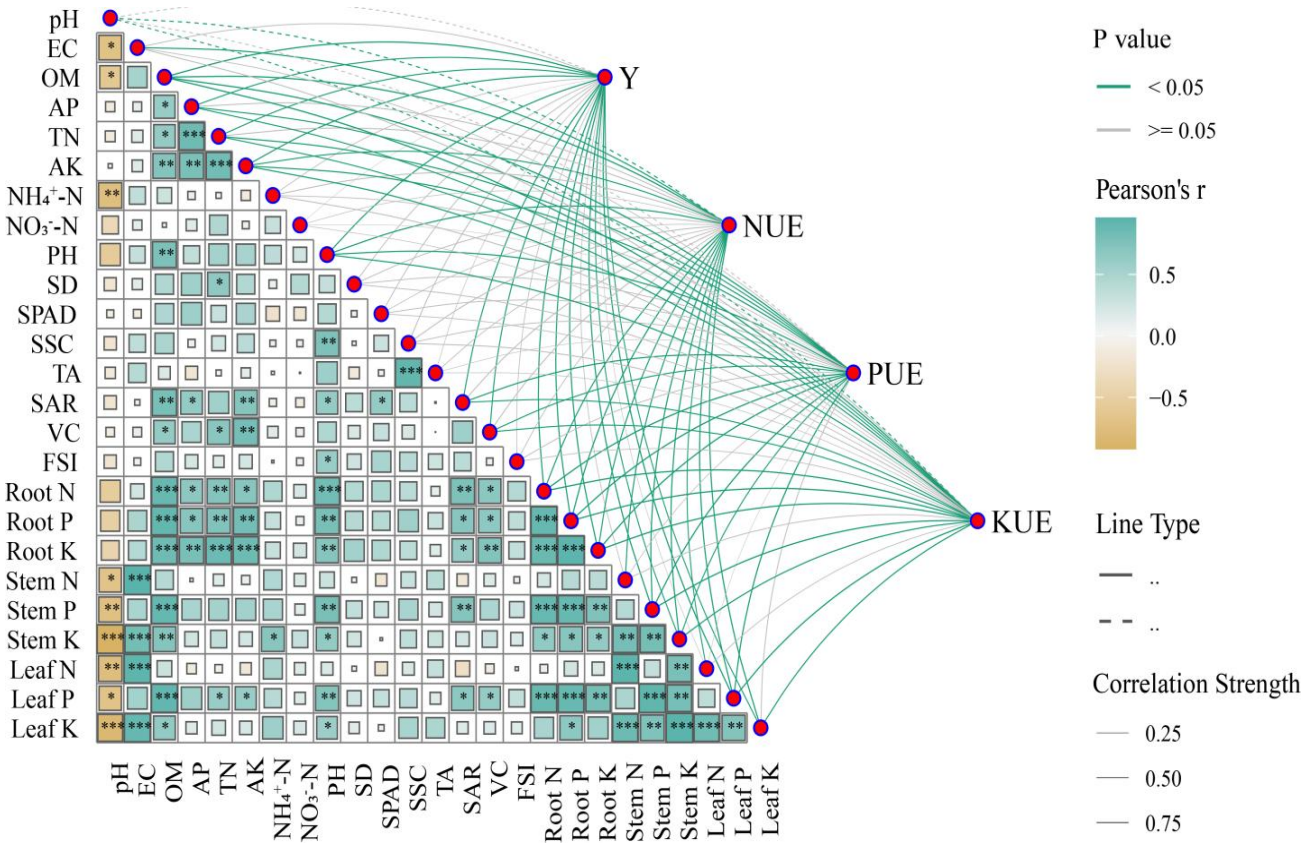


Fig. 6. Pearson correlation analysis among soil, growth, quality, and plant nutrients, and Mantel test between soil, growth, quality, and plant nutrients with yield and fertilizer use efficiency under different fertilization treatments in 2024.
Note: * indicates $p<0.05$; ** indicates $p<0.01$; *** indicates $p<0.001$.

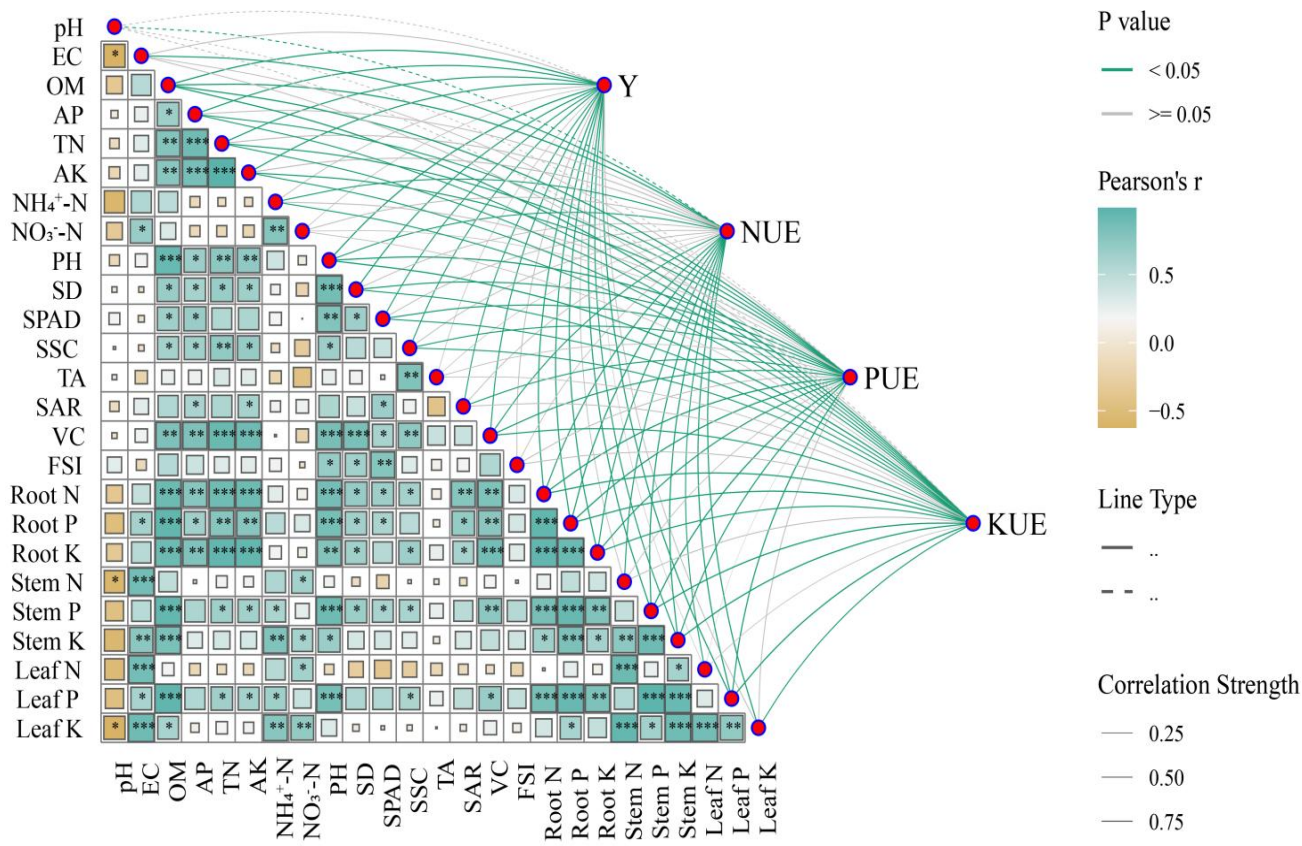


Fig. 7. Pearson correlation analysis among soil, growth, quality, and plant nutrients, and Mantel test between soil, growth, quality, and plant nutrients with yield and fertilizer use efficiency under different fertilization treatments in 2025.
Note: * indicates $p<0.05$; ** indicates $p<0.01$; *** indicates $p<0.001$.

Discussion

Fertilizer application clearly influenced plant growth, nutrient buildup, yield, and fruit quality in open-field tomatoes. (Li *et al*., 2025). The combined use of optimized fertilization and a soil conditioner (T4) enhanced nutrient use efficiency and productivity, outperforming conventional fertilization.

Plant N, P, and K accumulation is significantly influenced by fertilization practices (Wang *et al*., 2019). In the present study, T4 raised N, P, and K accumulation in tomato plants and also increased SPAD values. This indicates that the treatment improves plant nutrient status and photosynthetic performance, likely reflecting synergistic interactions between rhizosphere nutrient availability and plant physiological processes. In addition, Fulvic acid has been reported to promote dry matter accumulation, enhance photosynthetic pigments, and improve plant stress resistance (Li *et al*., 2019). Consistent with Zhou *et al*., (2025) findings, in the present study, SPAD values under T4 at maturity were higher than under T2. However, some studies have reported no significant effect of fulvic acid on SPAD values (Wadas *et al*., 2020), which may be related to differences in crop type and fertilization methods. In the present study, under unified irrigation and optimized fertilization, the fulvic acid-containing soil conditioner was applied repeatedly to the root zone through fertigation, enabling it to function as both a rhizosphere regulator and a nutrient source. Differences in the site of action and duration of effectiveness between these approaches may have altered nutrient uptake responses and SPAD values formation. Overall, T4 showed a stable positive effect on SPAD values. We acknowledge that interannual differences in rainfall and temperature may have contributed to the absolute variations in yield and quality between 2024 and 2025, although T4 consistently gave the highest values in both years.

Sugars are important indicators of internal fruit quality. Vitamin C content reflects the nutritional quality of fruits and vegetables and serves as a common measure of fruit quality (Kader *et al*.,2008). Fanourakis *et al*., (2025) emphasized that interannual variation in fruit quality under open-field conditions should be interpreted as the result of the combined effects of management practices and environmental conditions, which is consistent with the interannual response patterns observed in this study. In our experiment, fruit samples were collected at the same maturity stage; therefore, differences in SSC and VC were mainly attributable to fertilization treatments. The results showed that, in both 2024 and 2025, SSC, VC, and yield under T4 (optimized fertilization + soil conditioner) were superior to those under T2 and T3 , which is generally consistent with Zhou *et al*., (2025). This may be associated with the combined improvement of the root-zone environment under optimized fertilization and soil conditioner application (Lv *et al*., 2022). However, the magnitude of improvement varied between years, pointing to climatic influences (temperature, rainfall, light.) More work is needed on how seasonal mineral nitrogen dynamics, root traits, and microbial community features affect growth, yield, and fruit quality in open-field tomatoes under different fertilization regimes.

These soil improvements likely enhanced root nutrient uptake and sustained leaf photosynthesis, which in turn supported higher yield and better fruit quality. Soil nutrient status is closely tied to tomato yield and quality. Excessive chemical fertilizer application can damage soil structure, reduce FUE, and negatively affect yield and quality. Optimized fertilization improves nutrient uptake, yield, soil balance, and FUE (Yang *et al*., 2023; Zhang *et al*., 2024). In this work, optimized fertilization increased soil OM (as concentration) and along with N, P, and K contents, these findings are consistent with those of Zhao *et al*., (2023). Fulvic acid ranks as a key active part of soil conditioners. Unlike cereal crops, tomato is harvested repeatedly over months, so the sustained nutrient supply from fulvic acid matters more. It helps improve soil structure, raise nutrient availability, and boost root growth (Qi *et al*., 2018). The improved nutrient uptake under T4 may be attributed to the chelating effect of fulvic acid on P and K, together with reduced root-zone EC that alleviates salt stress. These changes likely promoted root function and leaf photosynthesis, supporting both yield and VC accumulation. Direct evidence on root physiology and microbial interactions was not collected, but our results are consistent with previous reports (Qi *et al.*, 2018). Liu *et al*., (2021) reported, the lower NO_3^--N content observed in the surface soil under fulvic acid treatment may be attributed to enhanced root uptake and improved rhizosphere conditions, resulting in greater nitrogen utilization by plants rather than accumulation in soil. The present study reached similar findings.

In this study, the optimized fertilization + soil conditioner treatment significantly increased AP and AK contents and OM concentration for the 0-60 cm depth, and this pattern was consistent in both 2024 and 2025. Soil nutrient contents generally decreased with increasing soil depth, this indicates that each treatment primarily improved the nutrient environment within the main root distribution layer, which is conducive to root uptake and the subsequent formation of yield and quality. A distinct vertical distribution pattern was observed, with relatively higher values for the 0-20 and 40-60 cm depth, particularly for OM. This may be related to root uptake, nutrient cycling, and organic matter input dynamics (Jobbágy *et al*., 2001; Rong *et al*., 2025). The relatively large increase in OM observed in this study can be explained by the low initial fertility of the newly cultivated soil, which has a high potential for nutrient accumulation (Li *et al*., 2021). Under such conditions, relatively large proportional increases are expected. Although the relative increase appears substantial, the absolute increase falls within the range reported in previous studies. Previous studies have shown that newly reclaimed soils exhibit low fertility and high responsiveness to organic inputs, with increases of 173.29% to 214.50% in OM concentration observed under commercial organic fertilizer treatments (Li *et al*., 2021). Long-term experiments show that organic amendments can raise soil organic carbon (SOC) by 64.90-126.60% (Rong *et al*., 2025). Also, treatments without a soil conditioner still had clear increases in soil OM. This suggests that fertilizer input and starting soil

conditions were the main drivers behind OM buildup. Additionally, this study was conducted on newly cultivated land with very low baseline fertility. Therefore, the large relative increases observed (in OM, yield, and nutrient contents) are likely specific to such low-fertility conditions. In mature, high-fertility soils, the same treatments would probably yield smaller relative gains, and the need for a soil conditioner may differ. Consequently, our findings are directly applicable to similar newly cultivated or low-fertility fields. Whether these results hold for soils with higher initial fertility or longer cultivation histories needs further testing. In this study, cutting back on nitrogen lowered NH_4^+-N and NO_3^--N in the topsoil. This effect might come from better nitrogen availability and less leaching loss, which in turn improves nitrogen use efficiency (Wang *et al*., 2013; Qu *et al*., 2020).

In summary, T4 used less fertilizer plus a soil conditioner and raised yield and quality under local conditions; the conditioner added extra benefit (Jin *et al*., 2025). This finding is consistent with the result of Jin *et al*., (2025). However, several limitations should be acknowledged. The findings are based on two years of field data (2024-2025), which is insufficient to clarify long-term effects of fertilization treatments. In addition, the experiment was conducted under a single soil type, a single cultivar, and specific open-field climatic conditions, and the results may also be influenced by interannual climatic variation. Therefore, testing these findings over more years and in more places remains necessary to see if they are stable and broadly applicable. Future work will compare these results with tomato studies from other major production regions.

Conclusion

Through a two-year field experiment, this study systematically evaluated the effects of optimized fertilization combined with a soil conditioner on soil quality, plant growth, yield, quality, and fertilizer use efficiency of open-field tomatoes.

(1) In terms of soil quality, the T4 treatment effectively increased nutrient contents within the top 0-60 cm of soil. In the topsoil (0-20 cm), versus conventional fertilization, TN, AP, and AK contents increased by a two-year average of 19.65%, 5.53%, and 25.86%, respectively, while OM concentration increased by 33.42% and EC was decreased by 21.45%. In the 20-40 cm layer, TN, AP, and AK contents were increased by averages of 14.23%, 3.29%, and 24.50%, respectively, while OM concentration increased by 15.30% and EC was decreased by 18.50%. In the 40-60 cm layer, TN, AP, and AK contents increased by averages of 25.54%, 8.45%, and 12.44%, respectively, while OM concentration increased by 49.96% and EC decreased by 31.05%.

(2) Regarding plant growth, yield, and quality, the T4 treatment promoted PH, SD, and SPAD value across all growth stages and enhanced root nutrient storage capacity. At maturity, PH, SD, and SPAD values increased by a two-year average of 6.18%, 10.04%, and 21.50%, respectively, compared with conventional fertilization. For yield and quality, this treatment raised two-year average yield by 26.21% and single fruit weight by about 16.00%, though the increase in single fruit weight was significant only in 2025. Compared to conventional fertilization, it also improved SSC by 9.99%, SAR by 8.11%, and VC by 26.55%, with year-specific significance: SSC only in 2025, SAR only in 2024, and VC in both years.

(3) In terms of fertilizer use efficiency, the T4 treatment showed significant improvements, with comprehensive enhancements in PFP, FUE, and AE of nitrogen, phosphorus, and potassium, with particularly prominent gains for phosphorus and potassium. Compared with conventional fertilization, nitrogen, phosphorus, and potassium PFP was increased by two-year averages of 45.14%, 42.27%, and 60.13%, respectively. Nitrogen, phosphorus, and potassium FUE were increased by averages of 4.52%, 1.21-fold, and 57.24%, respectively, while nitrogen, phosphorus, and potassium AE increased by averages of 1.50-fold, 1.45-fold, and 1.76-fold, respectively.

(4) Future research should conduct long-term localized monitoring to verify the applicability and stability of this approach under different soil types and interannual climatic variation, and to further optimize the approach in combination with economic benefit analyses. A cost-benefit comparison between optimized and conventional fertilization will be included in that assessment.

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