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Effects of Biochar and Dicyandiamide on Root Traits, Yield, and Soil N_2O Emissions of Greenhouse Tomato Under a Biogas Slurry Hole Irrigation System

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Abstract

To explore fertilization strategies that achieve both high yield and emission reduction in greenhouse tomato production, a two-season experiment was conducted in autumn 2023 and spring 2024 under equal nitrogen input. Seven treatments were established: conventional fertilization (CK1), biogas slurry alone (CK2), 0.5% biochar + biogas slurry (T1), 2% biochar + biogas slurry (T2), dicyandiamide + biogas slurry (T3), 0.5% biochar + biogas slurry + dicyandiamide (T4), and 2% biochar + biogas slurry + dicyandiamide (T5). The effects of each treatment on tomato root traits, yield, irrigation water use efficiency (IWUE), partial factor productivity of nitrogen (PFPN), and soil N_2O emissions were systematically evaluated. An analytic hierarchy process (AHP) was applied for comprehensive assessment. The results showed that fertilization treatments significantly affected tomato root traits ($p < 0.05$), with T5 exhibiting the best performance in root length, average diameter, total surface area, total volume, and root activity, all significantly higher than CK1. T5 also achieved the highest yield in both seasons, with increases of 8.13% (autumn 2023) and 10.19% (spring 2024) over CK1. Moreover, T5 showed superior IWUE (475.38 kg ha^{-1} mm^{-1}) and PFPN (405.92 kg kg^{-1}). In terms of environmental performance, T5 significantly reduced soil N_2O flux, with the largest reduction reaching 16.16%, particularly during the peak emission stages in the flowering and fruit-setting periods. The AHP-based comprehensive evaluation confirmed that T5 had the highest overall weight with satisfactory matrix consistency. In conclusion, compared with conventional fertilization, the integrated T5 treatment increased tomato yield by up to 10.19% and reduced cumulative N_2O emissions by up to 16.16%, highlighting its potential as a feasible fertilization pathway and technical reference for low-carbon and sustainable agriculture.

Keywords: N_2O emissions; biochar; dicyandiamide; equal nitrogen input; water and nitrogen use efficiency

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1. Introduction

With the rapid development of facility agriculture globally, greenhouse tomatoes, as a high-yield and high-efficiency economic crop, play a crucial role in ensuring year-round vegetable supply and improving agricultural productivity. Facility cultivation systems commonly adopt high-input, high-density production models, often accompanied by substantial chemical fertilizer application, subsequently causing ecological and environmental issues such as soil nutrient imbalance, deterioration of the rhizosphere environment, and increased greenhouse gas emissions [1]. Under persistent high-yield production requirements, nitrogen fertilizer application frequently exceeds the actual absorption capacity of tomatoes, yet nitrogen utilization efficiency remains as low as 20–35%, leading to substantial nitrogen losses through leaching, volatilization, and transformation processes [2]. Biogas slurry, a by-product of anaerobic fermentation from livestock manure and vegetable waste, is rich in organic matter and multiple nutrients, making it a valuable tool for promoting the resourceful utilization of agricultural wastes [3]. In greenhouse vegetable production, biogas slurry has the potential to partially substitute chemical fertilizers, thereby reducing dependence on synthetic fertilizers. However, due to the diverse forms and high mobility of nitrogen in biogas slurry, improper application practices can easily lead to nitrogen leaching and nitrous oxide (N_2O) emissions, thereby affecting the practical effectiveness of emission reduction and efficiency enhancement [4]. Against the backdrop of current facility agriculture development, it is imperative to explore optimized management strategies that improve the utilization efficiency of biogas slurry while simultaneously controlling environmental risks.

In recent years, various soil amendments have garnered widespread attention and have been extensively studied regarding nitrogen loss and greenhouse gas emissions associated with biogas slurry application. Biochar, an organic material characterized by its porous structure and high carbon stability, has been demonstrated to enhance soil nitrogen retention capability, thus reducing nitrogen leaching and volatilization losses due to its excellent adsorption and nutrient-retention properties and its capacity to improve soil physicochemical characteristics [5]. Biochar has also shown promising results in regulating greenhouse gas emissions. Zhou et al. [6] found that biochar application significantly reduced N_2O emissions during the wheat-growing season within a rice–wheat rotation system but had no significant impact during the rice-growing season. Biochar effectively reduces soil N_2O emissions by inhibiting N_2O production during nitrification and denitrification, promoting the reduction of N_2O to N_2, and directly adsorbing N_2O [7,8]. In terms of soil biological ecology, biochar supports plant root development and improves soil microbial community structures. Research by Ding et al. [9] indicated that biochar initially significantly increased $^{15}NH_4^+$ content by 45% but subsequently inhibited the microbial nitrogen remineralization process due to high pH and low soluble carbon content. Dicyandiamide (DCD), another widely used nitrogen regulator, primarily slows nitrification by inhibiting the conversion of ammonium to nitrate, thereby mitigating N_2O production risks from the source [10]. For instance, Yang et al. [11] reported that adding DCD alone to compost significantly inhibited NH_4^+-N conversion to NO_2^--N, reducing N_2O emissions by 31.79%. Moreover, the combined application with phosphogypsum further decreased N_2O emissions by lowering compost pH. Similarly, Jiang et al. [12] suggested that surface broadcasting combined with mixing methods of DCD application achieved superior emission reduction effects. Taken together, the combined application of biochar and DCD in biogas slurry systems is expected to synergistically improve soil nutrient utilization efficiency, regulate nitrogen transformation processes, and effectively mitigate greenhouse gas emissions through physical adsorption and chemical inhibition mechanisms. However, research on their combined effects under hole irrigation conditions remains limited, particularly regarding comprehensive impacts on root traits, yield performance, and nitrogen emissions in greenhouse tomato cultivation systems.

Based on the above research background, this study aims to elucidate the regulatory effects of biochar and DCD under biogas slurry hole irrigation systems on root traits, yield performance, and soil N_2O emissions in greenhouse tomatoes. It also investigates the mechanisms of action of the two regulatory materials when applied individually and in combination. Through different treatment settings, systematic assessments of root structural characteristics, root vitality, yield formation processes, and soil N_2O emission flux responses are conducted to reveal the potential of combined regulatory measures for emission reduction and efficiency enhancement under facility agriculture conditions. The findings of this research are expected to provide theoretical foundations and technical support for the efficient recycling of biogas slurry resources in facility vegetable cultivation, while simultaneously offering practical approaches to the establishment and promotion of green, low-carbon agricultural models, thereby possessing significant ecological and practical value.

2. Materials and Methods

2.1. Experimental Site Description

The experiment was conducted from August 2023 to July 2024 at the greenhouse water and fertilizer integrated demonstration site located in Gouyashan, Qilihe District, Lanzhou City, Gansu Province, China (36°2′23″ N, 103°42′39″ E). The region is characterized by a continental semi-arid climate with an elevation of 1875 m, a mean annual temperature of 10.9 °C, and average annual precipitation of 328 mm. According to the Classification and Codes for Chinese Soil (GB/T 17296-2009), the soil used in this experiment was classified as loessial soil. Prior to the experiment, the average soil bulk density of the plough layer (0–60 cm) was measured as 1.28 g cm^{-3}, with a pH of 7.48, organic matter content of 12.93 g kg^{-1}, ammonium nitrogen content of 11.36 mg kg^{-1}, and nitrate nitrogen content of 126.97 mg kg^{-1}.

2.2. Experimental Materials

The tested crop was tomato (*Solanum lycopersicum* L.) cultivar "Fenyan 734" characterized by high yield and excellent quality. The biogas slurry used was primarily derived from vegetable residues, with a pH of 8.06, alkali-hydrolyzed nitrogen of 0.888 g L^{-1}, total nitrogen of 0.956 g L^{-1}, total phosphorus of 0.054 g L^{-1}, and total potassium of 0.229 g L^{-1}. The biochar used had a fixed carbon content of 650 g kg^{-1}, available phosphorus of 10.2 g kg^{-1}, available potassium of 55.65 g kg^{-1}, bulk density of 0.19 g cm^{-3}, specific surface area of 9 m^2 g^{-1}, total porosity of 67.03%, aeration porosity of 12.87%, water-holding porosity of 61.10%, pH of 10.24, and cation exchange capacity of 60.8 mol kg^{-1}. The dicyandiamide (DCD) used was analytical grade with a nitrogen content of 67%. Fertilizers used included urea (N 46%), phosphate fertilizer (P_2O_5 12%), and potassium fertilizer (K_2O 50%).

2.3. Experimental Design

The experiment comprised plots measuring 6.0 m × 4.0 m, each with 7 ridges per plot, and a total of 3 identical plots, covering an area of 72 m^2. The local typical ridge-furrow plastic mulching cultivation method was adopted, with single ridges forming an arched cross-section (ridge width 0.3 m, height 0.2 m, row spacing 0.6 m, plant spacing 0.6 m). Each ridge was considered a replicate, totaling 21 ridges. To prevent water infiltration between plots, impermeable membranes were buried around each plot to a depth of 1 m, with protective rows established along the perimeter. Each ridge contained 8 plants, achieving a planting density of 23,333 plants ha^{-1}. The experiment followed a randomized block design with seven treatments under equal nitrogen input: conventional fertilization (CK1), biogas slurry alone (CK2), 0.5% biochar + biogas slurry (T1), 2% biochar + biogas slurry

(T2), dicyandiamide + biogas slurry (T3), 0.5% biochar + biogas slurry + dicyandiamide (T4), and 2% biochar + biogas slurry + dicyandiamide (T5). The total nitrogen input for each treatment was maintained at 390 kg ha^{-1}. Nitrogen fertilizer was partially replaced by biogas slurry according to its nitrogen content, and potassium and phosphorus fertilizers were applied at rates of 648 and 22 kg ha^{-1}, respectively. Prior to the experiment, 130 kg ha^{-1} of nitrogen fertilizer was applied as basal fertilizer. In CK1, basal potassium and phosphorus fertilizers were 216 kg ha^{-1} and 7 kg ha^{-1}, respectively, with the remaining fertilizer amounts applied in two subsequent applications. Except for CK1, all other treatments supplemented fertilizer deficiencies with biogas slurry. DCD was applied at 10% of the total nitrogen application.

Water–biogas slurry-integrated hole irrigation was employed [3], where two holes (diameter 5 cm, depth 7 cm) were placed 5 cm from both sides of the plant root zone along the ridge, and the water–biogas slurry mixture was applied into the holes and allowed to infiltrate for root uptake (hereafter referred to as "hole irrigation"). Irrigation frequency was every 2 days. Irrigation amounts were determined by cumulative evaporation from a φ20 cm evaporation pan positioned at crop canopy height. Water input was calculated by subtracting biogas slurry volume from total irrigation volume, ensuring equal irrigation volumes for all treatments. Irrigation volume was calculated using Equation (1) [13]:

$$W = \mathrm{K}_p \times \mathrm{S} \times E_p \tag{1}$$

where W represents irrigation volume (mL); $\mathrm{K_p}$ is the crop-pan coefficient (0.85); S is the irrigation control area (1800 cm^2); E_p is evaporation from the pan (mm).

2.4. Sample Collection and Measurement

2.4.1. Tomato Root Traits

Root samples were collected at maturity from three representative plants per treatment. Complete root systems were collected, washed, scanned, and analyzed for root length, average diameter, total surface area, and total volume using a root scanner and image analysis system. Root activity was determined by the TTC method [14].

2.4.2. Tomato Yield Measurement

Yield measurements were performed during fruit maturity (30 October to 15 December 2023; 25 May to 9 July 2024). Three randomly selected plants per treatment were harvested, and fruit weights were recorded to determine total yield.

Irrigation water use efficiency (IWUE, kg ha^{-1} mm^{-1}) was calculated using Equation (2) [15]:

$$IWUE = \frac{Y}{I} \tag{2}$$

where Y is tomato yield (kg ha^{-1}), and I is the total irrigation volume (mm).

Partial productivity of nitrogen fertilizer (PFPN, kg kg^{-1}) was calculated using Equation (3) [15]:

$$PFPN = \frac{Y}{N_t} \tag{3}$$

where Y is tomato yield (kg ha^{-1}), and N_t is the total nitrogen application (kg ha^{-1}).

2.4.3. Soil N_2O Collection and Measurement

Soil gases were collected in situ using a static chamber method consisting of two parts, a chamber and a base (manufactured by Phdmate Co., Ltd., Suzhou, China). The chamber was made of 5 mm thick polyvinyl chloride (PVC) with an outer diameter of 31.5 cm × 40 cm, externally insulated with sponge and reflective thermal insulation film.

The top of the chamber was equipped with a thermometer and fan for temperature measurement and gas mixing. The stainless-steel base was installed in the soil between two tomato seedlings on the ridge center immediately upon transplanting, remaining until harvest. The base was embedded to a depth of 8–10 cm in the soil with a 3 cm deep groove on the top to place the chamber, which was sealed with water during sampling. Gas samples were collected on days 1, 3, and 7 after tomato seedling recovery and subsequently every 14 days throughout the growing period. Sampling occurred between 09:30 and 10:30 AM; a 60 mL gas sample was collected at 0, 10, 20, and 30 min after chamber closure using a syringe with a three-way valve. Samples were stored at room temperature in aluminum foil sampling bags prior to analysis. Gas concentrations were analyzed using an Agilent gas chromatograph. Greenhouse gas fluxes were calculated using the following formula [10]:

$$F = \rho \times h \times \frac{dc}{dt} \times \frac{273.15}{(273.15 + T)} \times 60 \tag{4}$$

where F is the greenhouse gas flux (mg m^{-2} h^{-1}); ρ is the density of the greenhouse gas under standard conditions (for N_2O, ρ = 1.964 g L^{-1}); h is the height of the static chamber (m); dc/dt is the rate of change in greenhouse gas concentration in the chamber (ppm min^{-1}); T is the average temperature in the chamber during sampling (°C); and 60 is the conversion factor from minutes to hours.

The cumulative greenhouse gas emission (M, kg ha^{-1}) was calculated using

$$M = \Sigma\left(\frac{F_i + F_{i+1}}{2} \times d \times 24\right)/100 \tag{5}$$

where F_i and F_{i+1} are gas fluxes (mg m^{-2} h^{-1}) at two consecutive sampling periods; d is the number of days between sampling periods; and 24 is the conversion factor from hours to days.

2.5. Analytic Hierarchy Process Comprehensive Evaluation

The Analytic Hierarchy Process (AHP) is a systematic multi-criteria decision-making method that structures complex multi-objective decisions into hierarchical models consisting of goal, criteria, and sub-criteria or alternatives. It involves pairwise comparison of elements to quantify subjective judgments, calculate local weights, and determine global rankings for optimal decision-making. AHP was used to comprehensively evaluate tomato root traits, yield, and environmental impacts as follows [16]:

(1) Construction of a hierarchical model: The complex problem was divided into three levels—goal, criteria, and alternatives.

(2) Creation of a judgment matrix: Pairwise comparisons of the importance between elements at each level formed the judgment matrix for subsequent weight calculations. The comparison values used a scale from 1 to 9 and their reciprocals, indicating the relative importance of each element.

$$B = \begin{bmatrix} b_{11} & b_{12} & \dots & b_{1n} \\ b_{21} & b_{22} & \dots & b_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ b_{n1} & b_{n2} & \dots & b_{nn} \end{bmatrix} \tag{6}$$

(3) Single-level sorting and consistency test: The consistency index (CI) was first calculated using $CI = \lambda_{\max} - n/(n - 1)$, where $\lambda_{\max}$ is the maximum eigenvalue and n is the order of the judgment matrix. The consistency ratio (CR) was then calculated

using $CR = CI/RI$, where RI is the average random consistency index corresponding to matrix order n. A $CR < 0.10$ indicated acceptable consistency.

2.6. Data Analysis

Data processing was conducted with Microsoft Excel 2016. Graphics and correlation analyses ($p < 0.05$) were generated using Origin 2021. One-way ANOVA was performed in IBM SPSS Statistics 25, and mean comparisons were carried out with Duncan's multiple range test at the 0.05 significance level. Hierarchical diagrams were produced in Microsoft Visio 2010.

3. Results and Analysis

3.1. Effects of Different Treatments on Tomato Root Traits

To clarify the comprehensive impacts of different fertilization methods on root morphological structure and physiological activity, this study systematically measured and analyzed root length, average diameter, total surface area, total volume, and root activity during the autumn of 2023 and spring of 2024 (Table 1). Results indicated significant differences among treatments ($p < 0.05$), with the combined application of biochar, DCD, and biogas slurry (T5) performing best across most parameters. Treatment T5 achieved the greatest root length in both seasons (4688.40 cm on average), significantly higher than other treatments. Treatments T4 and T2 followed, with root lengths of 4239.49 cm and 4002.70 cm, respectively, while conventional fertilization (CK1) had the shortest root length (3443.90 cm). Average root diameter significantly increased under treatments T5 (1.530 mm) and T4 (1.477 mm), far surpassing CK1 (0.803 mm) and CK2 (0.924 mm), indicating enhanced mechanical support and nutrient transport capacities. Regarding root surface area and total volume, T5 treatment reached 2253.50 cm^2 and 86.33 cm^3, respectively, markedly higher than other treatments ($p < 0.05$), particularly in total volume, approximately 4.92 times higher than CK1. Root activity was also optimal under T5 (213.63 $\mu g\ g^{-1}\ h^{-1}$), significantly outperforming CK1 (134.79 $\mu g\ g^{-1}\ h^{-1}$). Treatments T4 (190.74 $\mu g\ g^{-1}\ h^{-1}$) and T2 (178.71 $\mu g\ g^{-1}\ h^{-1}$) similarly showed enhanced root activity compared to controls. Single applications of biochar or DCD (T1, T3) improved root activity marginally, highlighting the synergistic effects of combined treatments. Overall, T5 consistently outperformed other treatments in all five root parameters, demonstrating significant positive effects with stable performance over both seasons, indicating substantial application value.

Table 1. Effects of different treatments on root traits of greenhouse tomato.

Experimental Period	Treatments	Root Length (cm)	Root Average Diameter (mm)	Total Surface Area (cm^2)	Total Root Volume (cm^3)	Root Activity ($\mu g\ g^{-1}\ h^{-1}$)
Autumn 2023	CK1	3396.16g	0.752b	802.26g	15.09g	133.15g
	CK2	3564.08f	0.873ab	976.89f	21.32f	152.16f
	T1	3814.42d	0.967ab	1157.86d	27.98d	159.11e
	T2	3954.97c	1.158ab	1438.47c	41.65c	177.07c
	T3	3640.58e	0.906ab	1035.18e	23.43e	165.98d
	T4	4191.75b	1.426ab	1876.42b	66.87b	189.10b
	T5	4640.66a	1.479a	2155.48a	79.71a	211.99a
Spring 2024	CK1	3491.64g	0.8543bc	936.64g	20.00g	136.42g
	CK2	3659.56f	0.975b	1120.28f	27.30f	155.43f
	T1	3909.90d	1.069b	1312.07d	35.05d	162.38e
	T2	4050.44c	1.260ab	1602.92c	50.50c	180.34c
	T3	3736.05e	1.008b	1181.99e	29.77e	169.25d
	T4	4287.23b	1.528ab	2056.48b	78.54b	192.37b
	T5	4736.14a	1.581a	2351.52a	92.95a	215.26a

Note: Different letters within the same column indicate significant differences among treatments.

3.2. Effects of Different Treatments on Tomato Yield, Irrigation Water Use Efficiency (IWUE), and Partial Factor Productivity of Nitrogen (PFPN)

According to Table 2, Treatment T5 yielded the highest tomato production in both autumn 2023 and spring 2024 (139,260.0 kg ha^{-1} and 158,310.0 kg ha^{-1}, respectively), whereas Treatment CK1 produced the lowest yields (128,790.0 kg ha^{-1} and 143,670.0 kg ha^{-1}, respectively). Yield rankings for both seasons were consistent: T5 > T4 > T3 > T2 > T1 > CK2 > CK1. Compared to CK1, yields increased by 0.96–8.13% (autumn 2023) and 0.50–10.19% (spring 2024) under CK2 and T1–T5 treatments. IWUE was highest under T5 (475.38 kg ha^{-1} mm^{-1} and 472.49 kg ha^{-1} mm^{-1}) and lowest under CK1 (439.64 kg ha^{-1} mm^{-1} and 428.79 kg ha^{-1} mm^{-1}). PFPN similarly peaked in T5 (357.08 kg kg^{-1} and 405.92 kg kg^{-1}), while CK1 was lowest (330.23 kg kg^{-1} and 368.38 kg kg^{-1}).

Table 2. Effects of different treatments on yield, irrigation water use efficiency, and partial factor productivity of nitrogen fertilizer in greenhouse tomato.

Treatments		CK1	CK2	T1	T2	T3	T4	T5
Autumn 2023	Yield (kg ha^{-1})	128,790.0 ± 120.3g	130,020.0 ± 135.6f	131,490.0 ± 138.4e	131,760.0 ± 168.2d	132,030.0 ± 155.3c	136,860.0 ± 178.4b	139,260.0 ± 180.2a
	IWUE (kg ha^{-1} mm^{-1})	439.64 ± 10.36f	443.84 ± 9.27e	448.86 ± 13.62d	449.78 ± 13.28cd	450.70 ± 15.02c	467.19 ± 15.47b	475.38 ± 16.03a
	PFPN (kg kg^{-1})	330.23 ± 8.74e	333.38 ± 8.77d	337.15 ± 9.06c	337.85 ± 6.20c	338.54 ± 12.15c	350.92 ± 13.47b	357.08 ± 13.89a
Spring 2024	Yield (kg ha^{-1})	143,670.0 ± 166.2g	144,390.0 ± 170.5f	145,020.0 ± 175.4e	147,930.0 ± 200.7d	148,350.0 ± 238.1c	153,060.0 ± 210.9b	158,310.0 ± 264.3a
	IWUE (kg ha^{-1} mm^{-1})	428.79 ± 6.25f	430.94 ± 7.04e	432.82 ± 8.13d	441.51 ± 12.37c	442.76 ± 11.08c	456.82 ± 14.16b	472.49 ± 15.22a
	PFPN (kg kg^{-1})	368.38 ± 14.62f	370.23 ± 17.41e	371.85 ± 18.04d	379.31 ± 18.22c	380.38 ± 10.25c	392.46 ± 22.18b	405.92 ± 25.37a

Note: Different letters within a row indicate significant differences among treatments. Data are shown as mean ± standard deviation (n = 3).

3.3. Effects of Different Treatments on Soil N_2O Emission Flux from Greenhouse Tomato

As shown in Figure 1, similar patterns of N_2O emission flux were observed during both autumn 2023 and spring 2024. During the seedling stage (days 1–35), N_2O emission fluxes gradually increased in both seasons. However, as the tomato plants transitioned into the flowering and fruit-setting stages, a rapid increase in N_2O emissions was observed. In autumn 2023, emissions rose rapidly from day 35, peaking on day 49. The CK1 treatment exhibited the highest N_2O emission flux (186.29 µg m^{-2} h^{-1}), whereas the T5 treatment had the lowest (130.28 µg m^{-2} h^{-1}). Similarly, in spring 2024, emissions increased significantly from day 49, peaking on day 63. Treatment T2 showed the highest flux (180.44 µg m^{-2} h^{-1}), while T5 again had the lowest (126.66 µg m^{-2} h^{-1}). Following these peaks, N_2O emissions declined gradually across all treatments until harvest.

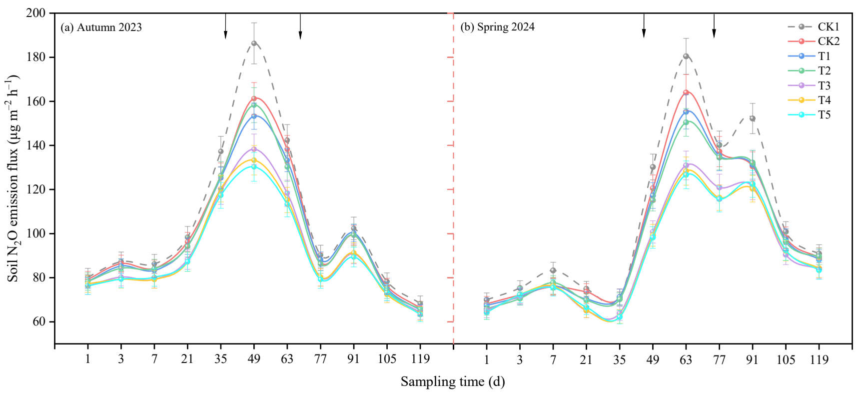

Figure 1. Effects of different treatments on N_2O emissions from greenhouse tomato soil. The black arrows indicate the timing of fertilizer application. Data are shown as mean ± standard deviation (n = 3).

Compared with CK1, treatments CK2, T1–T5 reduced N_2O emission fluxes by 4.85%, 6.51%, 6.56%, 12.86%, 13.63%, and 14.53%, respectively, in autumn 2023; and by 5.83%, 7.49%, 8.24%, 15.27%, 16.04%, and 16.16% in spring 2024. Additionally, compared to CK2, treatments T1–T3 showed reductions of 1.74%, 1.80%, and 8.42% in autumn 2023, and 1.76%, 2.56%, and 10.02% in spring 2024, respectively. Emission fluxes under T2 and T4 treatments were further reduced compared to T1 by 0.06% and 7.62% (autumn 2023) and 0.81% and 9.24% (spring 2024). Treatment T5 further reduced N_2O fluxes compared to T2 and T4 by 8.53% and 1.04% (autumn 2023) and by 8.63% and 0.15% (spring 2024), respectively.

3.4. Key Root Traits Affecting Yield and Soil N_2O Emissions in Greenhouse Tomato

To scientifically select suitable indicators for evaluating root traits in greenhouse tomatoes, this study analyzed the correlation between tomato yield, soil N_2O emissions, and root traits under equal nitrogen inputs and various external amendments using hole irrigation (Figure 2). Results indicated highly significant correlations ($p < 0.01$) between root length (RL), root average diameter (RAD), total surface area (RSA), total root volume (RB), and soil N_2O emissions, with root activity (RA) showing the strongest correlation ($p < 0.001$). Additionally, tomato yield was significantly correlated ($p < 0.05$) with RL, RAD, RSA, and RB. Considering biological significance, RL reflects the spatial expansion capacity essential for water and nutrient uptake; RAD represents root structural characteristics affecting mechanical support and nutrient transport; RA indicates physiological activity including nutrient uptake, metabolic function, and stress tolerance. Consequently, RL, RAD, and RA were identified as key indicators for the comprehensive evaluation of tomato root traits.

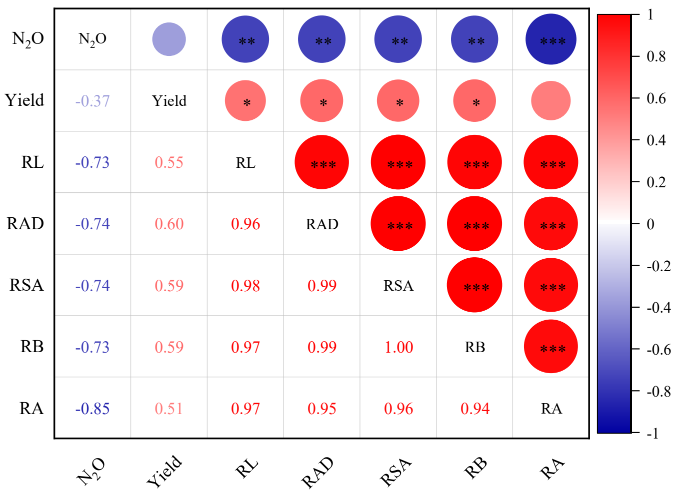

Figure 2. Correlation analysis of greenhouse tomato yield, soil N_2O fluxes, and root traits. *, **, and *** denote significance levels of $p \leq 0.05$, $p \leq 0.01$, and $p \leq 0.001$, respectively.

3.5. Multi-Indicator Comprehensive Evaluation of Greenhouse Tomato Based on AHP

Roots serve as a crucial link between crop yield and environmental metabolism. By regulating root traits, it is possible to enhance yield and environmental performance concurrently, promoting efficient and environmentally friendly agriculture. This study employed the Analytic Hierarchy Process (AHP) using tomato yield, irrigation water use efficiency (IWUE), partial factor productivity of nitrogen (PFPN), soil N_2O emissions, RL, RAD, and RA as evaluation indices to assess comprehensive effects of different external amendments under hole irrigation.

First, a hierarchical structure model comprising three levels, including the Goal (A), Criteria (B), and Alternatives (C), was constructed (Figure 3). Level B criteria included tomato yield (B1), irrigation water use efficiency (B2), partial factor productivity of nitrogen (B3), soil nitrous oxide emissions (B4), root length (B5), root average diameter (B6), and root activity (B7). Alternatives level C consisted of treatments CK1 (C1), CK2 (C2), T1 (C3), T2 (C4), T3 (C5), T4 (C6), and T5 (C7). According to the guidelines of the Analytic Hierarchy Process, comprehensive evaluation questionnaires were distributed among teachers and undergraduate and postgraduate students, achieving a valid response rate of 97.5%. Subsequently, statistical analyses were conducted to construct judgment matrices (Table 3), calculate synthesized weights for each criterion, and perform consistency tests (Table 4).

Table 3. Judgment matrix of comprehensive evaluation factors.

A-B	B1	B2	B3	B4	B5	B6	B7	Weight	Parametric Testing
B1	1.0000	2.0000	2.0000	1.0000	5.0000	5.0000	3.0003	0.2550	
B2	0.5000	1.0000	1.0000	0.5000	3.0003	3.0003	2.0000	0.1398	
B3	0.5000	1.0000	1.0000	0.3333	5.0000	5.0000	3.0003	0.1715	$\lambda_{max} = 7.1783$
B4	1.0000	2.0000	3.0000	1.0000	4.0000	4.0000	3.0003	0.2599	$CI = 0.0297$
B5	0.2000	0.3333	0.2000	0.2500	1.0000	1.0000	0.5000	0.0468	$CR = 0.0218$
B6	0.2000	0.3333	0.2000	0.2500	1.0000	1.0000	0.5000	0.0468	
B7	0.3333	0.5000	0.3333	0.3333	2.0000	2.0000	1.0000	0.0801	
B1-C	C1	C2	C3	C4	C5	C6	C7	Weight	Parametric testing
C1	1.0000	0.5000	0.3333	0.2500	0.2000	0.1667	0.1429	0.0081	
C2	2.0000	1.0000	0.5000	0.3333	0.2500	0.2000	0.1667	0.0118	
C3	3.0000	2.0000	1.0000	0.5000	0.3333	0.2500	0.2000	0.0178	$\lambda_{max} = 7.1973$
C4	4.0000	3.0000	2.0000	1.0000	0.5000	0.3333	0.2500	0.0269	$CI = 0.0329$
C5	5.0000	4.0000	3.0000	2.0000	1.0000	0.5000	0.3333	0.0405	$CR = 0.0242$
C6	6.0000	5.0000	4.0000	3.0000	2.0000	1.0000	0.5000	0.0606	
C7	7.0000	6.0000	5.0000	4.0000	3.0000	2.0000	1.0000	0.0894	
B2-C	C1	C2	C3	C4	C5	C6	C7	Weight	Parametric testing
C1	1.0000	1.0000	1.0000	1.0000	1.0000	0.5000	0.5000	0.0161	
C2	1.0000	1.0000	1.0000	1.0000	1.0000	0.5000	0.5000	0.0161	
C3	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.5000	0.0178	$\lambda_{max} = 7.1282$
C4	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0196	$CI = 0.0214$
C5	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0196	$CR = 0.0157$
C6	2.0000	2.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0240	
C7	2.0000	2.0000	2.0000	1.0000	1.0000	1.0000	1.0000	0.0265	
B3-C	C1	C2	C3	C4	C5	C6	C7	Weight	Parametric testing
C1	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.5000	0.0218	
C2	1.0000	1.0000	1.0000	1.0000	1.0000	0.5000	0.5000	0.0200	
C3	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.5000	0.0218	$\lambda_{max} = 7.1187$
C4	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0241	$CI = 0.0198$
C5	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0241	$CR = 0.0145$
C6	1.0000	2.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0268	
C7	2.0000	2.0000	2.0000	1.0000	1.0000	1.0000	1.0000	0.0329	
B4-C	C1	C2	C3	C4	C5	C6	C7	Weight	Parametric testing
C1	1.0000	1.0000	1.0000	1.0000	0.3333	0.3333	0.2000	0.0188	
C2	1.0000	1.0000	1.0000	1.0000	0.3333	0.3333	0.2000	0.0188	
C3	1.0000	1.0000	1.0000	1.0000	0.5000	0.5000	0.3333	0.0224	$\lambda_{max} = 7.2022$
C4	1.0000	1.0000	1.0000	1.0000	1.0000	0.5000	0.5000	0.0266	$CI = 0.0337$
C5	3.0000	3.0000	2.0000	1.0000	1.0000	0.5000	0.3333	0.0379	$CR = 0.0248$
C6	3.0000	3.0000	2.0000	2.0000	2.0000	1.0000	0.5000	0.0522	
C7	5.0000	5.0000	3.0000	2.0000	3.0000	2.0000	1.0000	0.0832	
B5-C	C1	C2	C3	C4	C5	C6	C7	Weight	Parametric testing
C1	1.0000	0.5000	0.5000	0.3333	0.5000	0.2000	0.1667	0.0021	
C2	2.0000	1.0000	1.0000	0.5000	1.0000	0.3333	0.1667	0.0036	
C3	2.0000	1.0000	1.0000	0.5000	2.0000	0.3333	0.2000	0.0044	$\lambda_{max} = 7.1705$
C4	3.0000	2.0000	2.0000	1.0000	2.0000	0.5000	0.3333	0.0066	$CI = 0.0284$
C5	2.0000	1.0000	0.5000	0.5000	1.0000	0.5000	0.3333	0.0039	$CR = 0.0209$
C6	5.0000	3.0000	3.0000	2.0000	2.0000	1.0000	0.5000	0.0100	
C7	6.0000	6.0000	5.0000	3.0000	3.0000	2.0000	1.0000	0.0163	
B6-C	C1	C2	C3	C4	C5	C6	C7	Weight	Parametric testing
C1	1.0000	0.5000	0.5000	0.3333	0.5000	0.2000	0.1429	0.0020	
C2	2.0000	1.0000	1.0000	0.5000	1.0000	0.3333	0.1667	0.0036	
C3	2.0000	1.0000	1.0000	0.5000	2.0000	0.3333	0.2000	0.0044	$\lambda_{max} = 7.1593$
C4	3.0000	2.0000	2.0000	1.0000	2.0000	0.5000	0.3333	0.0065	$CI = 0.0265$
C5	2.0000	1.0000	0.5000	0.5000	1.0000	0.5000	0.3333	0.0038	$CR = 0.0195$
C6	5.0000	3.0000	3.0000	2.0000	2.0000	1.0000	0.5000	0.0099	
C7	7.0000	6.0000	5.0000	3.0000	3.0000	2.0000	1.0000	0.0166	
B7-C	C1	C2	C3	C4	C5	C6	C7	Weight	Parametric testing
C1	1.000	0.500	0.500	0.333	0.333	0.200	0.167	0.0032	
C2	2.000	1.000	0.500	0.333	0.333	0.250	0.167	0.0043	
C3	2.000	2.000	1.000	0.500	0.500	0.333	0.200	0.0060	$\lambda_{max} = 7.1911$
C4	3.000	3.000	2.000	1.000	2.000	0.500	0.333	0.0114	$CI = 0.0318$
C5	3.000	3.000	2.000	0.500	1.000	0.333	0.250	0.0091	$CR = 0.0234$
C6	5.000	4.000	3.000	2.000	3.000	1.000	0.500	0.0182	
C7	6.000	6.000	5.000	3.000	4.000	2.000	1.000	0.0279	

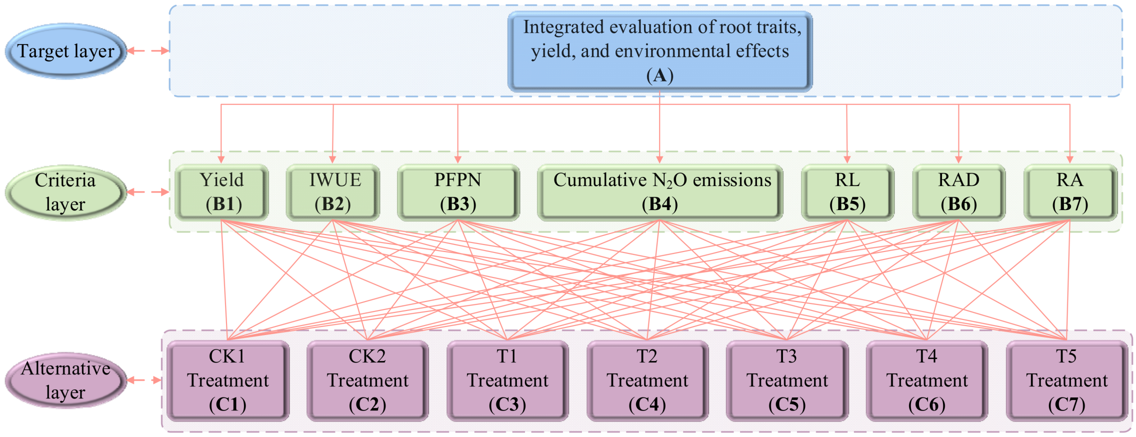

Figure 3. Hierarchical structure model for the comprehensive evaluation of root traits, yield, and environmental effects.

Table 4. Synthesized weights of elements at each level with respect to the goal level.

Treatments	Weight of Evaluation Indicators							Global Weight
	Yield (kg ha^{-1})	IWUE (kg ha^{-1} mm^{-1})	PFPN (kg kg^{-1})	Cumulative N_2O Emissions (kg ha^{-1})	Root Length (cm)	Root Average Diameter (mm)	Root Activity (μg g^{-1} h^{-1})	
CK1	0.0081	0.0161	0.0218	0.0188	0.0021	0.0020	0.0032	0.0134
CK2	0.0118	0.0161	0.0200	0.0188	0.0036	0.0036	0.0043	0.0142
T1	0.0178	0.0178	0.0218	0.0224	0.0044	0.0044	0.0060	0.0175
T2	0.0269	0.0196	0.0241	0.0266	0.0066	0.0065	0.0114	0.0222
T3	0.0405	0.0196	0.0241	0.0379	0.0039	0.0038	0.0091	0.0281
T4	0.0606	0.0240	0.0268	0.0522	0.0100	0.0099	0.0182	0.0394
T5	0.0894	0.0265	0.0329	0.0832	0.0163	0.0166	0.0279	0.0576

The overall consistency ratio for the alternatives was below 0.10, indicating reliable results. Treatments ranked by comprehensive effectiveness were T5 > T4 > T3 > T2 > T1 > CK2 > CK1. Treatment T5 (2.0% biochar + DCD + biogas slurry) exhibited the highest comprehensive weight (0.0576), demonstrating superior performance in yield enhancement, resource utilization, root improvement, and greenhouse gas emission reduction. Treatments T4 (0.5% biochar + DCD + biogas slurry) and T3 (DCD + biogas slurry) followed closely. Conversely, treatments without DCD (T1 and T2) had lower comprehensive weights, and treatments CK2 (biogas slurry alone) and CK1 (conventional fertilization) were least effective. Overall, adding DCD significantly enhanced comprehensive effectiveness, higher biochar doses were preferable, and single applications of biogas slurry without additional measures were limited in efficacy. Thus, T5 emerges as the optimal strategy for balancing root traits, yield, and environmental benefits in greenhouse tomato production.

4. Discussion

4.1. Effects of Different Treatments on Tomato Root Traits, Yield, and Water–Nutrient Use Efficiency

Different types of external amendments can enhance crop yield by promoting root development and improving nutrient uptake efficiency [17]. In this study, significant differences in tomato root traits were observed among different fertilization treatments ($p < 0.05$), with the combined application of biochar, dicyandiamide (DCD), and biogas slurry (T5) demonstrating optimal performance across most traits. Several reasons account for these improvements in root morphology and structure. Firstly, biochar application notably enhanced soil physicochemical properties [18]. The porous structure of biochar improves soil aeration and water retention, creating a loose, moist, and well-oxygenated environment favorable for root growth. Additionally, the alkaline properties of biochar help modulate soil pH, further facilitating root length and surface area development [19].

It is noteworthy that changes in soil pH not only affect root morphology but also play a crucial role in the transformation of nitrogen forms. An appropriate pH helps to reduce the excessive conversion of ammonium nitrogen (NH_4^+-N) to nitrate nitrogen (NO_3^--N), thereby enhancing nitrogen retention in the soil and reducing the risk of nutrient leaching [18]. Secondly, biogas slurry, as an organic nutrient source, contains abundant readily available nitrogen, phosphorus, potassium, and trace elements, providing sustained and adequate nutrient support to plant roots [20], thus enhancing stress resistance and ultimately increasing crop yields [21]. This mechanism aligns with the highest yields observed in T5 across both experimental seasons. Moreover, under consistent nitrogen and water inputs, T5 exhibited the highest irrigation water use efficiency (IWUE) and partial factor productivity of nitrogen (PFPN). Biochar improved nutrient utilization efficiency of biogas slurry through adsorption and slow-release mechanisms, enhancing soil aggregation and reducing nutrient losses [22]. Consequently, retention of macro-and micronutrients in the crop root zone increased significantly [23], substantially promoting root differentiation and expansion, particularly evident in root volume and surface area. Thirdly, DCD inhibited soil urease activity and nitrifying bacteria, slowing nitrogen transformation, reducing nitrogen volatilization and leaching, and ensuring stable nitrogen supply to roots [24]. This enhanced root nitrogen uptake capacity, contributing to thicker main roots and more extensive lateral root systems, reflected in improved average root diameter and volume. Lastly, this combined treatment favored beneficial rhizosphere microbial proliferation and activity. Biochar provided abundant habitat spaces for beneficial microbes, while biogas slurry served as a carbon source promoting microbial metabolism. Microbial activity facilitated the release of growth regulators such as indole acetic acid, indirectly enhancing root cell division and elongation, thus optimizing root morphology and improving root vitality [25].

4.2. Effects of Different Treatments on Soil N_2O Emissions from Greenhouse Tomato

During both experimental seasons, N_2O emission fluxes showed a gradual increase during the seedling stage (days 1–35) but significantly escalated as plants transitioned to the flowering and fruit-setting stages (days 36–72). Emission fluxes peaked during this period and gradually declined afterward until harvest. Several factors contributed to this observed trend in N_2O emissions. Firstly, during flowering and fruit-setting stages, enhanced nitrogen uptake and increased root activity accelerated soil nitrogen transformations. Ammonification and nitrification intensified, rapidly converting ammonium nitrogen (NH_4^+) into nitrate nitrogen (NO_3^-). Part of NO_3^- underwent reduction to N_2O in anaerobic or partially anaerobic environments due to denitrification. As N_2O is an intermediate denitrification product, increased nitrogen cycling directly elevated N_2O emissions [26]. Secondly, rising temperatures during spring 2024 necessitated increased irrigation frequency to sustain tomato water supply, maintaining moderate-to-high soil moisture conditions (60–80% field water capacity). Such conditions promote denitrification, facilitating nitrate reduction to N_2O or molecular nitrogen (N_2), significantly contributing to elevated N_2O emissions [27]. Enhanced root exudation during rapid growth released abundant organic acids and soluble organic carbon into the rhizosphere, providing ample electron donors for denitrifying microbial metabolism [28], thereby increasing microbial activity, population density, and N_2O production. Additionally, nitrogen fertilizer top-dressing increased inorganic nitrogen concentrations, supplying substrates for nitrification-denitrification processes. Coupled with irrigation, this water-nitrogen interaction led to intense short-term N_2O emission peaks [29]. Single chemical fertilizer applications caused substantial fluctuations in NO_3^- concentrations, often triggering pulse-like N_2O emissions and exacerbating emission intensity.

Treatment T5 consistently exhibited the lowest N_2O emissions across both experimental seasons. This outcome can be attributed to two primary factors. Firstly, the addition of biochar significantly improved soil aeration and structure, thereby reducing the anaerobic conditions required for denitrification and subsequently suppressing the reduction of NO_3^- to N_2O [30]. Concurrently, DCD, a nitrification inhibitor, effectively delayed NH_4^+ conversion to NO_3^-, minimizing substrate accumulation for denitrification [31]. Previous studies have shown that another commonly used nitrification inhibitor, nitrapyrin, can also influence nitrogen cycling by regulating soil pH and the composition of inorganic nitrogen, which in turn shapes the soil microbial community [32]. Compared with nitrapyrin, the effect of DCD is more direct, mainly manifested in slowing nitrogen transformation, while its potential role in microbial community regulation still warrants further investigation. This combined effect notably decreased nitrification and denitrification activities, thus reducing N_2O generation. Secondly, as a slow-release organic nitrogen source, biogas slurry moderately stabilized inorganic nitrogen concentrations, minimizing abrupt fluctuations. Its soluble organic carbon content favored microbial nitrogen assimilation, lowering nitrogen losses via nitrification–denitrification pathways [33]. In addition, an appropriate soil C/N ratio also plays an important role in nitrogen transformation processes. In the T5 treatment, the relatively balanced C/N ratio not only improved the soil microbial ecological environment but also promoted microbial immobilization of inorganic nitrogen and maintained the balance between organic nitrogen mineralization and immobilization. These effects further stabilized nitrogen transformation pathways and effectively reduced N_2O generation and emissions at the source [34].

4.3. Research Limitations and Tiered Practical Guidance

This study provides valuable insights into the integrated effects of different regulatory measures on tomato root traits, yield, and environmental performance, yet certain limitations remain. First, sampling and measurements were conducted only at the maturity stage, which can reflect the final outcomes but fail to capture the dynamic changes in root development across different growth phases. Future studies should therefore perform sequential sampling at key developmental stages such as seedling, flowering, and fruiting, in order to more systematically reveal the processes of nitrogen transformation and root morphological responses. Second, the maximum biochar application rate in this study was set at 2%. The results demonstrated significant benefits of biochar at this level in improving root structure, enhancing yield, and reducing emissions; however, the effects of rates exceeding 2% have not yet been verified. Given that high biochar dosages may substantially alter soil physicochemical properties and, under long-term accumulation, affect microbial communities and nitrogen cycling, this remains an important topic for future research. From a practical application perspective, the treatments can be categorized into a tiered recommendation framework based on their integrated performance. Tier 1 (highly integrated performance): T5, which performed best in terms of yield, resource-use efficiency, and environmental benefits. Tier 2 (efficient alternatives): T4 and T3, which, although slightly inferior to T5, still exhibit strong application potential under scenarios requiring a balance between input and effectiveness. Tier 3 (transitional options): T1 and T2, which showed limited overall effects. By contrast, CK1 and CK2 may serve as benchmarks for conventional management practices. Future research should also incorporate cost–benefit analysis, operational complexity, and emission–reduction priorities, thereby establishing a more practical and operable decision-making framework that can provide direct guidance for farmers and agricultural extension services.

5. Conclusions

Different fertilization treatments significantly influenced the root traits of greenhouse tomatoes ($p < 0.05$). Among them, the T5 treatment (2% biochar + biogas slurry + dicyandiamide) consistently exhibited superior performance across five key root parameters: root length, average diameter, total surface area, total volume, and root activity. These values were significantly higher than those observed under conventional fertilization. The results demonstrated that the T5 treatment achieved the highest tomato yield in both growing seasons, with increases of 8.13% in autumn 2023 and 10.19% in spring 2024 compared to the conventional treatment (CK1). Furthermore, T5 also showed the highest irrigation water use efficiency (475.38 kg ha^{-1} mm^{-1}) and partial factor productivity of nitrogen (405.92 kg kg^{-1}). In terms of environmental impact, T5 significantly reduced soil N_2O emissions across both seasons, with the largest reduction reaching 16.16%. Notably, T5 consistently maintained the lowest N_2O flux during the peak emission periods associated with tomato flowering and fruit setting.

To comprehensively assess the agronomic and environmental performance of each treatment, an analytic hierarchy process (AHP)-based evaluation model was constructed. The results indicated that T5 had the highest integrated weight score, and the consistency indices of the judgment matrices were within acceptable ranges. In summary, the T5 treatment demonstrated outstanding potential for improving yield and resource use efficiency while mitigating greenhouse gas emissions. These findings highlight its applicability for scaled adoption and offer valuable theoretical and practical support for the development of precision agriculture. Future studies should incorporate a comprehensive cost–benefit analysis to evaluate the economic feasibility of T5 treatment, thereby providing more robust guidance for large-scale implementation.

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