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The Influence of Organic and Inorganic Fertilizer Applications on Nitrogen Transformation and Yield in Greenhouse Tomato Cultivation with Surface and Drip Irrigation Techniques

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Abstract: Facility agriculture in China is facing the challenge of the excessive use of chemical fertilizers (nitrogen fertilizers), which hinder the development of sustainable and environmentally friendly agriculture. Optimizing nitrogen fertilizer allocation is essential to balance agricultural production and environmental concerns. The aim of this study was to determine the optimal organic fertilizer strategy for tomato cultivation under different irrigation methods. An experiment was conducted in a greenhouse, and two irrigation methods, surface irrigation (SI) and drip irrigation (SDI), were used during tomato growth. The fertilization treatments included urea alone (CK); 30%, 40%, and 50% chicken manure mixed with urea (FC1, FC2, FC3); and 50% cow manure and sheep manure mixed with urea (FB3, FS3). The results showed that the irrigation techniques and fertilization had significant effects on ammonia volatilization accumulation, soil mineral nitrogen content, and tomato yield and quality. Compared with the surface irrigation technique with the same amount of fertilizer application, the drip irrigation technique reduced the ammonia volatilization accumulation by a maximum of 76.40%. The SDIFC3 and SDIFB3 ammonia volatilization accumulation was as low as 5.24 (kg·hm^{-2}) and 7.61 (kg·hm^{-2}); the soil nitrate nitrogen content was reduced, and the tomato yield increased significantly by 17.11%. The SDIFC3 treatment achieved a maximum yield of 13,414 (kg·hm^{-2}), increased the tomato vitamin C and soluble sugar contents by 19.13% and 8.97%, and lowered the titratable acid content by as much as 30.51%. Under drip irrigation fertilization conditions, the SDIFC3 treatment showed lower ammonia volatilization accumulation and the highest tomato yield and quality compared to CK and the same proportion of organic fertilizer substitutes with cow and sheep manure. The increase in the proportion of organic fertilizers replacing chemical fertilizers resulted in a gradual decrease in ammonia volatilization accumulation and a gradual increase in the tomato yield and various qualities. The soil mineral N content, on the other hand, was significantly affected by irrigation, fertilizer application, and water–fertilizer interaction effects, with a tendency for the content to increase and then decrease after each fertilizer application. The mineral N content was lower with drip irrigation compared to surface irrigation, especially in the 10–20 cm soil layer than in the 0–10 cm layer. Increasing drip irrigation and organic fertilizer substitution significantly increased the vitamin C and soluble sugar contents in the tomatoes, while decreasing the titratable acid content.

Keywords: greenhouse tomato cultivation; organic fertilizer; urea; surface drip irrigation; ammonia volatilization; mineral nitrogen; tomato yield and quality

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1. Introduction

Tomatoes are one of the three major globally traded vegetables. In 2021, China's tomato cultivation area was 1.11 million hectares, with a production of 66.09 million tons, accounting for approximately one-third of the global tomato production. Additionally, greenhouse tomato cultivation holds a leading position, occupying 57.2% of the total area that is dedicated to facility vegetable cultivation in China [1]. However, the problems of energy consumption and environmental pollution caused by improper water and fertilizer management in facility-grown tomatoes was urgently addressed [2]. Therefore, the strategy of optimizing the use of water and fertilizer and regulating greenhouse gas emissions is used to balance the economic benefits and environmental friendliness of facility tomato cultivation.

Nitrogen is an important source of nutrients for crop growth, and nitrogen application is an indispensable and important agricultural measure for normal growth and for increasing tomato yield to improve its productivity [3]. Nitrogen inputs to cropping systems have increased rapidly over the past decades to meet the demand for food production [4]. From 2015 to 2020, global N fertilizer consumption increased by 1.5% per year, reaching 118.7 million tons in 2020 [5]. However, excessive nitrogen inputs brought about a series of environmental production problems, such as the greenhouse effect, soil acidification, a soil nitrogen surplus, water eutrophication, and soil quality degradation, which adversely affect the environment and human health [6]. Approximately 11.0 Tg (Terrogram)/year of nitrogen losses, primarily in the form of NH_3, occur as a result of nitrogen fertilizer application on soil surfaces [7,8]. Lost ammonia is the main source of PM2.5 [9,10]. In addition, emitted ammonia indirectly affects biodiversity deterioration, water eutrophication, and air pollution [11]. Therefore, it is particularly important to maintain facility-based agricultural production and reduce agroecological pollution by effectively reducing the amount of nitrogen fertilizer inputs.

As an organic nutrient source, organic fertilizers enter the soil to provide nutrients for crop growth and development, improve soil physicochemical properties, and increase soil water and fertility retention [10]. Organic fertilizer can improve soil structure, increase the number of aggregates, and promote the growth and development of crop roots [6,12]. Organic fertilizers are rich in organic matter and various amino acids, which enhance soil fertility [13]. A meta-analysis indicated in that organic fertilizers could increase tomato yields by 42.18%, and soluble solids, soluble sugars, lycopene, and vitamin C were increased by 11.86%, 42.18%, 23.95%, and 18.97%, respectively, when compared to the control group [14], which is in agreement with the studies of Yang et al. [15] and Sun et al. [16]. The appropriate proportion of organic fertilizer substitution reduces rhizosphere soil nitrate nitrogen leaching [17]. At the same time, ammonia volatilization can be reduced, and the quality of crops can be improved [18,19]. The use of organic fertilizer to replace inorganic nitrogen fertilizers enhances the soil microbial fixation of fertilizer nitrogen and reduces the soil mineral nitrogen content [20], while Xu et al. [21] showed that soil nitrate content increased significantly only in the proportion of a 50% versus a 100% organic fertilizer replacement. The use of chemical and organic fertilizers together is more beneficial and ensures sustainable production, and chemical fertilizers have fewer harmful effects on soil health and the environment [22]. As a traditional agricultural and farming country, China is rich in straw and livestock manure, which are important components of organic fertilizers [23]. However, current research focuses on the application of organic fertilizers to improve soil and crop yields, but lacks research on the ammonia volatilization pattern of organic fertilizers replacing chemical fertilizers in facility-grown vegetables and the response mechanism of crops under different irrigation modes, especially with the combination of the current advanced irrigation techniques that save water and fertilizers, such as drip irrigation and other related methods.

Irrigation constitutes a primary water supply for facility crop growth, particularly in high-water-demand crops like tomatoes, wherein the chosen irrigation technique influences the soil physicochemical attributes, nitrogen fertilizer transport, and ammonia volatilization dynamics [24,25]. Irrational irrigation practices contribute to a nitrogen loss of approximately 50–70%, aggravating ammonia volatilization; however, it has been shown that drip irrigation significantly reduces greenhouse gas emissions, reduces ammonium nitrogen levels in field water after fertilization, mitigates ammonia volatilization, and improves water and fertilizer utilization rates [26]. At present, drip irrigation technology has been widely promoted in China, and drip irrigation fertilization strategies can reduce the loss of nitrate and dissolved organic nitrogen in greenhouse vegetables by 25–90% and save nitrogen fertilizer inputs by 25–50% [27]. Overall, drip irrigation fertilization minimizes nitrogen leaching and soil ammonia volatilization losses and improves crop yield and water productivity [24]. Among the major organic fertilizers that are marketed and legislatively permitted for use in organic production systems in China, cow, sheep, and chicken manure organic fertilizers are particularly noteworthy, as most of them are applied to the soil surface or mixed into the soil at a high cost. However, few studies have been reported on whether the combined application of organic and inorganic fertilizers under drip irrigation affects soil ammonia volatilization and mineral nitrogen content, and whether organic fertilizers with different dosing ratios affect nitrogen conversion in the soil and the yield and quality of facility-grown vegetables. In this context, this study investigated the need to optimize water and fertilizer management in greenhouse tomato growing. In this research context, by focusing on the effects of different substitution ratios and different organic fertilizer types on key factors such as soil ammonia volatilization, mineral nitrogen content, and tomato yield and quality, we ask the central questions of this study: Can drip irrigation with organic fertilizer instead of chemical fertilizer effectively optimize water and fertilizer management in greenhouse tomato cultivation? Which type of organic fertilizer and which organic fertilizer/chemical fertilizer ratio is the most appropriate? Through these core questions, we pursued to explore the optimal water and fertilizer management strategies under different irrigation methods in order to achieve a harmonious balance between economic benefits and environmental responsibilities in greenhouse tomato cultivation.

2. Materials and Methods

2.1. Experimental Site

This study was carried out in a greenhouse at the Field Scientific Observatory for Agricultural Soil and Water Environment, located in Xinxiang City, Henan Province, China, under the Chinese Academy of Agricultural Sciences (latitude 35.27′ N, longitude 113.93′ E, altitude 73.2 m above sea level). The experimental area has a temperate continental climate with a mean annual temperature of 14.1 °C, a frost-free period of 220 days, a sunshine duration of 2398.8 h, and a mean precipitation of 587.9 mm, with drastic annual fluctuations and unstable seasonal distribution. The annual potential evapotranspiration was recorded as 2000 mm. The relative humidity in the greenhouse averaged at 58.1% throughout the year. The air temperature and crop evapotranspiration (ET_0) in the greenhouse during the tomato growth period are shown in Figure 1.

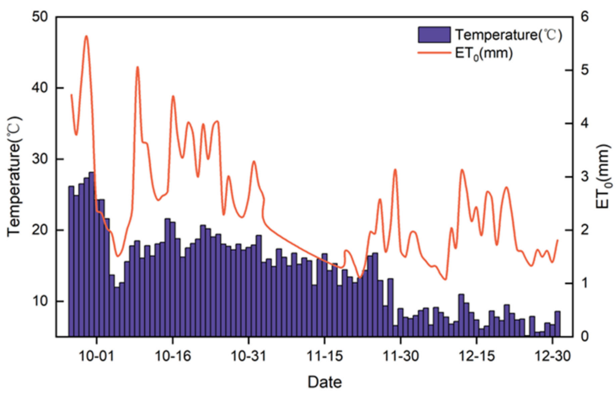

Figure 1. Variations in air temperature and crop evapotranspiration in the greenhouse during the tomato growth period.

2.2. Experimental Design

2.2.1. Test Soil

The test soil was collected from the Xinxiang Comprehensive Experimental Base of the Chinese Academy of Agricultural Sciences (latitude, 113°53′ E; longitude, 35°19′ N) at a depth of 0–20 cm. After collection, the soil was left to naturally air-dry and then thoroughly mixed to ensure homogeneity. The test soil was classified as sandy loam and underwent a meticulous process to eliminate any visible stones, fine roots, and biological residues. It was further sieved through a 5 mm mesh. Three test soil samples were selected for analysis, and the physical and chemical properties of the soils are detailed in Table 1.

Table 1. Basic physical and chemical properties of the test soil.

pH	**EC (1:5) (μS·cm^{-1})**	**OM %**	**AP (mg·kg^{-1})**	**AK (mg·kg^{-1})**	**TN (mg·kg^{-1})**
8.26 ± 0.13	325.2 ± 5.83	0.54 ± 0.12	8.41 ± 1.82	311 ± 3.05	970 ± 0.07

Note: OM refers to soil organic matter; AP refers to quick-acting phosphorus; AK refers to quick-acting potassium; TN refers to total nitrogen.

2.2.2. Experimental Design

The experiment involved the cultivation of tomato plants in pots, and it included two factors: the irrigation technique and fertilization. The irrigation methods were divided into two levels: surface irrigation (SI) and drip irrigation (SDI). The fertilizer treatments were determined according to local farmers' fertilization habits, including a single application of urea for the control group (CK) and the "organic fertilizer + formulated fertilizer" mode. Within the "organic fertilizer + formulated fertilizer" mode, three types of organic fertilizers were used: chicken manure, cattle manure, and sheep manure. Based on the types of organic fertilizers and their proportions with urea, five fertilization modes were established as follows: 30% chicken manure fertilizer + 70% urea fertilizer (FC1); 40% chicken manure fertilizer + 60% urea fertilizer (FC2); 50% chicken manure fertilizer + 50% urea fertilizer (FC3); 50% cattle manure fertilizer + 50% urea fertilizer (FB3); 50% sheep manure fertilizer + 50% urea fertilizer (FS3). These fertilizer treatments were combined at six levels. The experiment consisted of 12 treatments, each treatment was replicated five times, and each replication involved one pot and one tomato plant; there were 60 replications in the experiment.

The experimental trial was conducted utilizing the 'Jing Fan 404' tomato cultivar and spanned from 27 September 2022 to 10 January 2023. The experiment was carried out using polyvinyl chloride (PVC) pots with dimensions of a 32 cm outer diameter, a 29.5 cm inner diameter, a 26 cm bottom diameter, and 33.5 cm in height. Each pot was filled with 18.31 kg of soil, with a total of 60 pots used in the test.

Before transplanting, the basal fertilizer application included organic fertilizer and urea by following local practices. For the topdressing, three applications were carried out during the first, second, and third fruiting stages when the fruits reached the size of egg yolks. The same amount of nitrogen was applied for each topdressing. The nitrogen contents of the urea and the organic fertilizers are detailed in Table 2, and the fertilizer program is presented in Table 3. The experimental phosphorus and potassium fertilizers used were calcium superphosphate and potassium xanthate, with basal applications of 29 g/pot and 5.7 g/pot during each of the three fertilizer applications.

Table 2. Nitrogen content and C:N ratio of organic N fertilizers.

Treatments	**N %**	**C:N**
Control (urea)	46.00	0.43
Chicken manure	1.50	5.83
Cattle manure	0.50	18.36
Sheep manure	0.70	6.42

Table 3. Treatment and fertilizer regimen.

Irrigation Technology	Fertilizer Treatment	Fertilizer Application Ratio of Manure to Chemical Fertilizer	Base Fertilizer (g/pot)	Topdressing (g/pot)
Surface irrigation (SI)	CK	100% urea	Urea (14 g)	Urea (5.5 g)
	FC1	30% chicken + 70% urea fertilizer	Manure (830 g) + urea (1.5 g)	Urea (5.5 g)
	FC2	40% chicken + 60% urea fertilizer	Manure (1100 g) + urea (1.8 g)	Urea (4.1 g)
	FC3	50% chicken + 50% urea fertilizer	Manure (1380 g)	Urea (4.1 g)
	FB3	50% cattle + 50% urea fertilizer	Manure (4140 g)	Urea (4.1 g)
	FS3	50% sheep + 50% urea fertilizer	Manure (2960 g)	Urea (4.1 g)
Surface drip irrigation (SDI)	CK	100% urea	Urea (14 g)	Urea (5.5 g)
	FC1	30% chicken + 70% urea fertilizer	Manure (830 g) + urea (1.5 g)	Urea (5.5 g)
	FC2	40% chicken + 60% urea fertilizer	Manure (1100 g) + urea (1.8 g)	Urea (4.1 g)
	FC3	50% chicken + 50% urea fertilizer	Manure (1380 g)	Urea (4.1 g)
	FB3	50% cattle + 50% urea fertilizer	Manure (4140 g)	Urea (4.1 g)
	FS3	50% sheep + 50% urea fertilizer	Manure (2960 g)	Urea (4.1 g)

Other agricultural practices, such as disease and pest control and tillage measures, were conducted similarly to the conventional practice of cultivating tomatoes in facility vegetable fields.

2.2.3. Irrigation and Fertilization Methods

This experiment employed a water–fertilizer integration system for irrigation and fertilization. The fertilizers were fully dissolved in the fertilization device and applied simultaneously with the irrigation water. Both the drip irrigation and surface irrigation techniques were utilized. For the drip irrigation, the same fertilization treatment was connected through a drip irrigation pipe. Four drip arrows were strategically distributed around the plant to ensure uniform and efficient irrigation (Figure 2). In the case of surface irrigation, the pipe was connected to the capillary, allowing the water to flow freely. Throughout the experiment, the amount of irrigation water used in all treatments was consistently maintained.

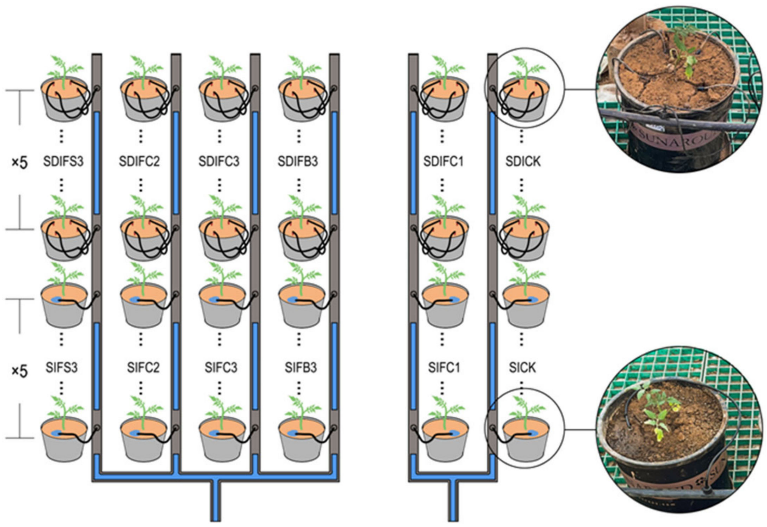

Figure 2. Experimental design and layout.

2.3. Monitoring Indicators and Analysis Methods

2.3.1. Soil Mineral Nitrogen

After each fertilizer application, three random soil samples per treatment were collected from the 0–10 cm and 10–20 cm soil horizons to determine the soil nitrate nitrogen (NO_3-N) and ammonium nitrogen ($NH_4{}^+$-N) concentrations. For the determination of soil mineral nitrogen, a 0.01 mol/L $CaCl_2$ solution was used for extraction. The contents of NH_4^+-N and NO_3-N in the soil samples were analyzed using a continuous flow analyzer with a sensitivity of 0.001 AUFS (Seal Analytical GmbH, Norderstedt, Germany) [28].

2.3.2. Determination of Ammonia Volatilization in Surface Soils

The surface soil ammonia volatilization was assessed using the aeration method [29]. The ammonia volatilization capture device consisted of a rigid polyvinyl chloride tube with a 10 cm inner diameter and 12 cm height. Two sponges, each with a 2 cm thickness and 10 cm diameter, were soaked uniformly in a solution of 10 mL of phosphoric acid and glycerol (prepared by mixing 50 mL of phosphoric acid and 40 mL of propanetriol, adjusted to a total volume of 1000 mL). These soaked sponges were then placed in the rigid plastic tube, with the lower sponge positioned 5 cm away from the tube's bottom and the upper sponge aligned with the tube's top to prevent interference from atmospheric ammonia gas.

A capture device was placed on the right side of each pot, the sponges were placed at 8:00 a.m. on the day of sampling, and samples were collected at 8:00 a.m. the next day, capturing ammonia for 24 consecutive hours, with consistent intervals between each sample for all treatments. During sampling, the upper sponge was replaced every 3–7 days depending on the circumstances. The lower sponge in the aeration device was removed and promptly transferred to a 500 mL plastic bottle, which was sealed to protect it from light. Simultaneously, it was replaced with another sponge that was soaked with fresh glycerol phosphate solution. The plastic bottle was immediately taken to the laboratory, and 300 mL of a 1.0 mol/L KCL solution was added to fully submerge the sponge. After shaking for 1 h, the leachate was extracted, and the ammonium nitrogen content was determined using a continuous flow analyzer to quantify the ammonia volatilization from the surface soil. The ammonia volatilization rate of the field soil was calculated using the following equation:

$$V = \mathrm{M} \times 10^{-2}/(\mathrm{A} \times \mathrm{D}) \tag{1}$$

The ammonia volatilization rate from the soil (V) is expressed in kg/(hm^2·d), where M is the average amount of NH_3-N measured per time by a single device of the aeration method (mg); A is the cross-sectional area of the capture device (m^2); and D is the time interval between each successive capture (d).

$$\mathrm{S} = 1/2 \sum_{i=1}^{n} (V_i + V_{i+1}) \times (T_i - T_{i-1}) \tag{2}$$

where S is the cumulative soil NH_3 volatilization (kg·hm^{-2}), n is the number of measurements taken after fertilizer application, T_i is the time after the fertilization measurement (in days), and V_i is the ammonia volatilization rate at the measurement (kg/hm^2).

2.3.3. Tomato Yield and Quality

Five replications were selected for each treatment to measure the tomato yield, which was derived by calculating the total mass of the first, second, and third fruit clusters on each plant and then converted to yield per hectare. Three replicates per treatment were selected to measure the tomato quality, including vitamin C, soluble sugars, and titratable acids. The tomato quality was determined using the following methods based on *Experiments in Plant Physiology* by Chen Gang [30]: The vitamin C content was quantified using 2,6-dichloroindophenol titration, while the soluble sugar content was assessed through anthrone colorimetry. Additionally, the titratable acid content was measured using alkaline titration.

2.4. Statistical Analysis

Data analysis was performed using SPSS software (version 21.0, IBM, Armonk, NY, USA), and graphical representations were created using Origin 2021b (Origin Lab Corporation, Northampton, MA, USA). To assess significant distinctions ($p \leq 0.05$) in the ammonia volatilization accumulation and the tomato yield and quality, a one-way analysis of variance (ANOVA) and Duncan's method were employed.

3. Results

3.1. Soil Ammonia Volatilization

3.1.1. Soil Ammonia Volatilization Rate

Following the initial fertilizer application, the soil's ammonia volatilization rate exhibited a notable surge, with the peak value significantly exceeding that of the subsequent two applications (Figure 3). The ammonia volatilization rate of the SDICK treatment started to increase after the first fertilizer application, reached a peak of 2.92 kg/(hm^2·d), and then decreased. In contrast, the other treatments experienced a gradual decline in ammonia volatilization rates, stabilizing approximately 10 days thereafter. Notably, ammonia volatilization rates were much higher for the SICK and SIFC1 treatments under surface-irrigated conditions (Figure 3a), with peaks of 4.28 kg/(hm^2·d) vs. 4.27 kg/(hm^2·d), respectively, while the SDICK treatment showed the highest rate under drip irrigation. Subsequent to the second and third fertilizer applications, the ammonia volatilization rate sharply ascended, reaching its zenith between the second and third day, before starting to decline (Figure 3).

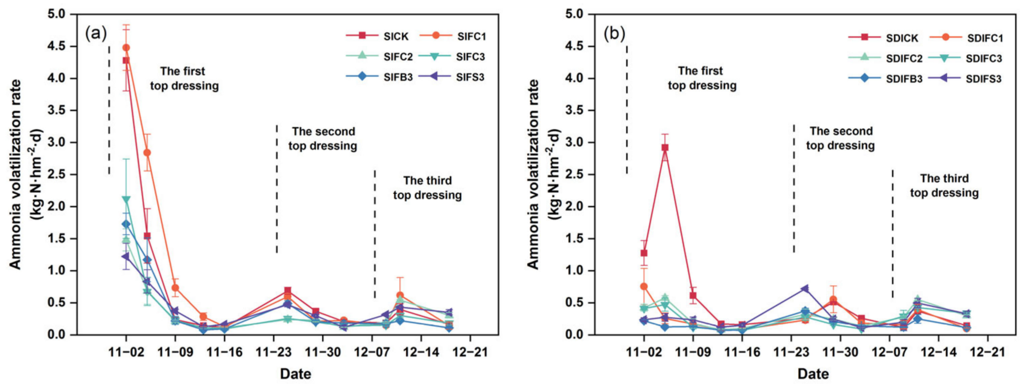

Figure 3. Ammonia volatilization after each topdressing under different irrigation conditions. (**a**) Ammonia volatilization rate from surface irrigation, (**b**) Ammonia volatilization rate from surface drip irrigation.

Under surface irrigation, the peak ammonia volatilization rate of each treatment appeared after the first topdressing, with the peak value in the SIFC1 treatment being the highest (4.48 kg/(hm^2·d)), and the peak in the SIFS3 treatment being the lowest (1.55 kg/(hm^2·d)). After the second topdressing, the peak values of SICK and SIFC1, SIFB3, and SIFS3 exhibited a descending order ($p \leq 0.05$). However, these peak values were significantly different from those of SIFC2 and SIFC3. After the third topdressing, the peak values of the SIFC1 and SIFS3 treatments became the highest and the lowest values, respectively. The peak ammonia volatilization rate of the SDICK and SDIFC1 treatments appeared later than other treatments after the second topdressing under drip irrigation. The peak rate of the SDIFS3 treatment was the largest, and the smallest one was 0.32 kg/(hm^2·d) for SDIFC3.

After the third topdressing, the variability of the peaks among the different topdressing treatments under drip irrigation became smaller compared with that of surface irrigation. The maximum ammonia volatilization peaks under drip irrigation were significantly lower than those under surface irrigation, with reductions of 31.72% and 83.16% for the CK and FC1 treatments, respectively, and reductions of 69.68%, 71.68%, 92.74%, and 74.72% for FC2, FC3, FB3, and FS3, respectively.

3.1.2. Cumulative Ammonia Volatilization Emissions

The different treatments had a significant effect ($p \leq 0.05$) on the cumulative volatilization of ammonia (Table 4). Significant differences were found between the surface-irrigated

CK treatments and the treatments with organic fertilizers, which reduced the ammonia volatilization accumulation by 28.28–42.67% compared to the CK treatments. Under the drip irrigation technique, all treatments were significantly different except for FC1 and FC2, which were not significantly different. Compared with the surface irrigation treatments, the drip irrigation treatments were effective at reducing the ammonia volatile accumulation under the same fertilization treatments, with the FC1 treatment showing the highest reduction of 76.40%, and the rest of the treatments showed decreases of 42.09–72.13%. Similar to the SDI treatment, the ammonia volatilization accumulation of the SIFC1, SIFC2, and SIFC3 treatments also decreased gradually with increases in the organic fertilizer applications, with a maximum decrease of about 54.22%.

Table 4. Ammonia volatilization accumulation under different treatments (a–e $p \leq 0.05$).

Treatments		Accumulation of NH_3 Volatilization ($kg \cdot hm^{-2}$)
SI	CK	27.30 ± 2.43 b
	FC1	34.19 ± 1.61 a
	FC2	16.58 ± 0.70 de
	FC3	15.65 ± 1.42 e
	FB3	18.15 ± 1.09 cd
	FS3	19.58 ± 0.77 c
SDI	CK	15.81 ± 0.28 a
	FC1	8.07 ± 0.88 c
	FC2	8.80 ± 0.21 c
	FC3	7.61 ± 0.51 d
	FB3	5.24 ± 0.23 e
	FS3	9.03 ± 0.43 b

3.2. Soil Mineral Nitrogen

The mineral nitrogen levels exhibited a consistent upward trajectory during the reproductive phase, registering an increase ranging from 164.06% to 1097.84% in the surface-irrigated setups, and from 104.53% to 325.17% in the drip-irrigated scenarios (Figure 4). Notably, during the fruit expansion stages of the first, second, and third spikes, the most substantial percentage augmentation in the mineral nitrogen content was observed in the SDIFC2, SDIFC1, and SDIFB3 treatments, with increases of 119.50%, 77.03%, and 24.94%, respectively.

In terms of the soil layers, the mineral nitrogen concentration within the 10–20 cm stratum generally trailed behind that of the 0–10 cm layer. Among the treatments, the SICK treatment exhibited the highest content, measuring 892.68 mg/kg. The magnitude of variation in the 10–20 cm soil layer was relatively small throughout the reproductive period, with SIFC3 showing the greatest variation in mineral N content at 67.99%, and SDIFC2 showing the least at 21.46%.

As the proportion of organic fertilizers gradually replacing the chemical fertilizers increased, the mineral nitrogen content of the 0–10 cm soil layer showed a decreasing trend. In the first fruit expansion stage, the mineral nitrogen content under the SDI conditions surpassed those under the SI conditions, peaking in the FC2 treatment; the other treatments remained lower than the CK treatment. In the subsequent second fruit expansion phase, the mineral nitrogen content exhibited lower increases under drip irrigation compared to surface irrigation, excluding FC1, and all treatments were below conventional irrigation levels. During the third fruit expansion phase, the mineral N content in the SDIFC3 treatment decreased, becoming smaller than that of the SIFC3 treatment, while other fertilizer treatments showed significantly higher mineral nitrogen contents under drip irrigation than surface irrigation. When contrasted with FC1, FC2, and FC3, the mineral nitrogen content displayed a decreasing trend as the proportion of organic fertilizer replacing chemical fertilizer increased.

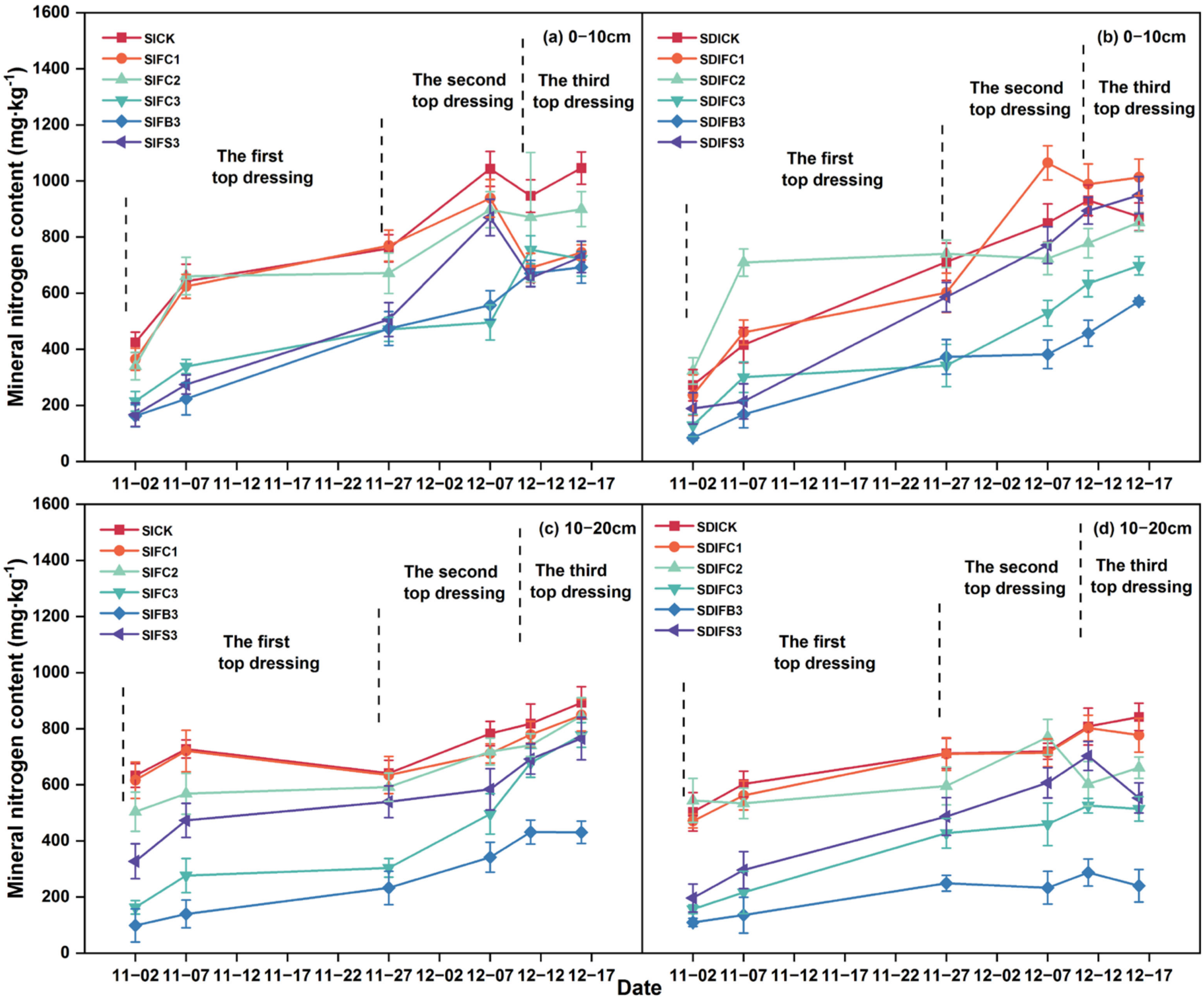

Figure 4. Mineral nitrogen content of soil under different treatments. (**a**) Mineral nitrogen content of surface irrigated 0–10 cm soil layers, (**b**) Mineral nitrogen content of surface irrigated 10–20 cm soil layers, (**c**) Mineral nitrogen content of surface drip-irrigated 0–10 cm soil layers, (**d**) Mineral nitrogen content of surface drip-irrigated 10–20 cm soil layers.

After tomato harvesting, the mineral nitrogen residues in the CK and FC2 treatments were significantly higher than those in the other treatments within the 0–10 cm soil layer under the SI technique. In addition, there were significant differences between the three treatments, CK, FC3, and FB3, and the remaining three treatments in the 10–20 cm soil layer ($p \leq 0.05$). Under the SDI technique, the mineral nitrogen contents of the FC3 and FB3 treatments were significantly lower than those of the other treatments within the 0–10 cm soil layer. The greatest variability in mineral nitrogen content within the 10–20 cm soil layer was observed between the CK and FB3 treatments. Mineral nitrogen residues were significantly lower in SDIFC3 and SDIFB3 using drip irrigation, while the rest of the fertilization treatments were not significantly different (Figure 5).

3.3. Tomato Yield and Quality

Compared to the surface irrigation levels, the drip irrigation levels resulted in yield reductions of 12.10% and 35.03% in the CK and FC1 treatments, respectively, while it was increased by 3.12–17.11% under the other treatments. Under surface irrigation conditions, the FC3 treatment had the highest yield (11,738 kg·hm^{-2}), but there was no significant difference in yield among the different fertilization treatments (Table 5).

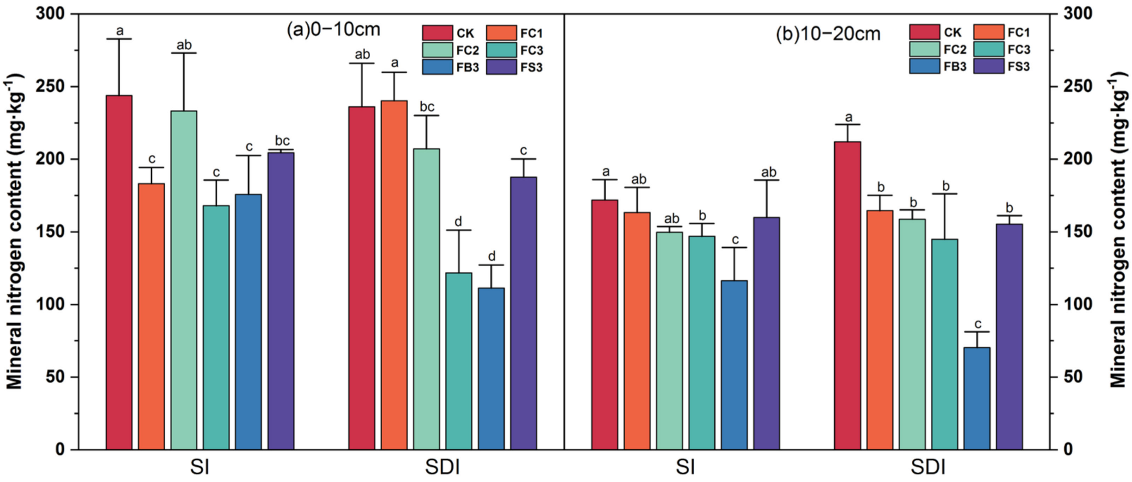

Figure 5. Residual mineral nitrogen content in soil under different treatments (a–d $p \leq 0.05$).

Table 5. Tomato yield and fruit quality under different treatments (a–e, $p \leq 0.05$).

Irrigation Technology	Fertilizer Treatment	Yield ($kg \cdot hm^{-2}$)	Vitamin C (mg/100 g)	Acidity/%	Soluble Sugar/%
SI	CK	9719.28 a	0.94 c	0.81 b	10.64 b
	FC1	11,506.35 a	1.19 b	0.72 bc	11.90 ab
	FC2	9761.85 a	1.20 b	0.70 bc	10.89 b
	FC3	11,738.55 a	1.15 b	0.54 a	12.24 a
	FB3	10,153.24 a	1.55 a	0.59 ab	11.26 ab
	FS3	10,262.03 a	1.53 a	0.64 ab	11.27 ab
SDI	CK	8542.95 de	1.01 a	0.70 ab	10.65 bcd
	FC1	7475.76 e	1.20 ab	0.53 cd	11.81 ab
	FC2	10,066.73 cd	1.26 b	0.81 a	9.91 cd
	FC3	13,414.50 a	1.37 b	0.51 cd	11.06 bc
	FB3	10,337.84 bc	1.26 b	0.41 d	9.66 d
	FS3	12,017.79 ab	1.33 b	0.59 bc	12.28 a

Under drip irrigation, the tomato yield from the plants treated with organic fertilizer combined with chemical fertilizer was significantly higher than that from the plants treated with a single fertilizer (except for the SDIFC1 treatment). The yield of plants treated with chicken manure increased significantly with the increase in the proportion of organic fertilizer ($p < 0.05$). The yield of the SDIFC treatment was the highest, which was significantly higher than that of the SDIFB3 and SDIFS3 treatments, and was 3.00–8.73% higher (Table 5).

Under surface irrigation, the vitamin C content was significantly higher in the organic fertilizer application treatments compared to the CK treatments. Under drip irrigation, the vitamin C contents of the tomatoes decreased under the FB3 and FS3 treatments, but increased by 0.84–19.13% under other treatments (Table 5). The vitamin C content of the tomatoes treated with chicken manure combined with chemical fertilizer was significantly affected by the irrigation conditions and the proportion of chicken manure combined with the chemical fertilizer (Table 5). Under surface irrigation, the vitamin C content increased first and then decreased with the increase in the chicken manure application ratio, while under drip irrigation, the content showed the opposite trend.

The maximum titratable acid content of tomato fruits was observed from the SDIFC2 and SDICK treatments, while the minimum was from the FB3 treatment. Surface irrigation (SI) reduced the titratable acid content at the FC2 level, and drip irrigation (SDI) significantly reduced the titratable acid content under the rest of the fertilizer application levels. Notably, under surface irrigation conditions, these levels in the 30% chicken manure replacement treatment were significantly higher than in the 40–50% chicken manure replacement treatments. Under drip irrigation conditions, the titratable acid content of the tomatoes with the 40% chicken manure replacement treatment was the highest, significantly higher than the with the replacement rates of 30% and 50%. Drip irrigation (SDI) generally exhibited a reduced tomato soluble sugar content, except for in the FS3 treatment. The soluble sugar concentration of the SDIFS3 treatment was the highest under SDI, increasing by 8.96% compared to the SIFS3 treatment. Comparing the SICK and SDICK treatments, most of the treatments with applications of organic fertilizer showed increased soluble sugar contents, and with the increase in the amount of organic fertilizer, the soluble sugar content showed a trend of decreasing and then increasing, with FC3 showing the highest content.

3.4. Correlation Analysis

The soil ammonia volatile emissions were significantly positively correlated with the inorganic nitrogen content in both the 0–10 cm and 0–20 cm soil layers (Figure 6). This indicates that the combination of irrigation technology and organic fertilizer replacing chemical fertilizer could lead to an increased accumulation of inorganic nitrogen in the surface layer of the soil, which in turn triggers soil ammonia volatile emissions. However, it was observed that the accumulation of inorganic nitrogen in the soil layer at the end of the reproductive period was not conducive to the formation and improvement of the tomato yield and fruit quality. The tomato yield and titratable acid content showed a significant positive correlation. This suggests that the application of organic fertilizer instead of a certain proportion of chemical fertilizer under both surface irrigation and drip irrigation conditions can lead to an improvement in the tomato yield and an increase in the titratable acid content of the fruits. This finding implies that the use of organic fertilizer in combination with chemical fertilizer can enhance the yield and taste quality of tomatoes.

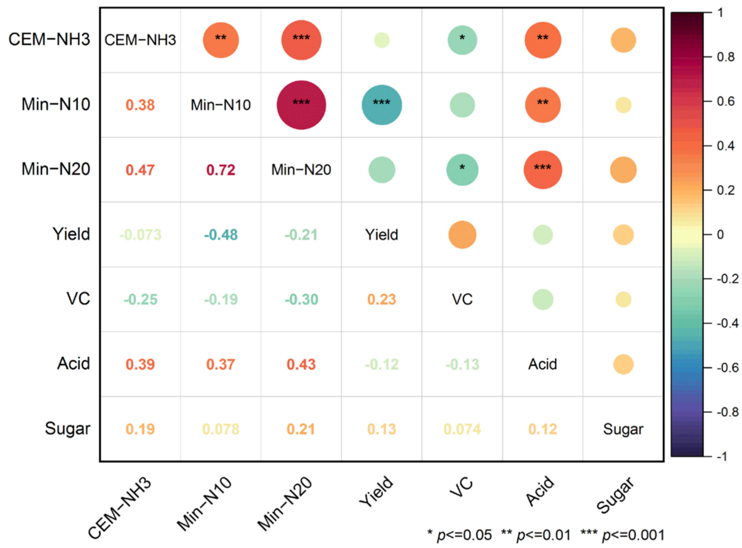

Figure 6. Correlation thermogram. Note: I means irrigation technology; F means fertilizer treatment; CEM-NH_3 means cumulative emission of NH_3; Min-N10 and Min-N20 mean residual mineral nitrogen of the 0–10 cm and 10–20 cm soil layers, respectively, and VC means vitamin C.

4. Discussion

4.1. Effect of Different Water and Fertilizer Managements on Ammonia Volatilization Rates and Ammonia Volatilization Losses

Ammonia volatilization serves as a notable route for soil nitrogen loss, with its extent being impacted by the nitrogen fertilizer's type and applied quantity [31–33]. In this study, it was observed that the application of organic fertilizer under drip irrigation significantly reduced ammonia volatilization emissions compared to surface irrigation with urea application alone, consistent with previous studies [31,34–36]. In drip irrigation fertilization, urea is dissolved in the irrigation water and applied to the soil, which accelerates the hydrolysis of nitrogen fertilizer, shortens the ammonia volatilization cycle, and reduces the loss of nitrogen fertilizer, thus reducing the ammonia volatilization rate and cumulative emissions. Additionally, drip irrigation delivers dissolved nitrogen fertilizer directly to the crop roots through drip arrows, resulting in a smaller surface soil wetting area and reduced NH_4^+ concentration, further lowering the cumulative ammonia volatilization.

Organic fertilizers have been shown to be effective in reducing ammonia volatilization losses [37,38]. Manure organic fertilizer reduces the soil pH due to the production of organic acids by soil microorganisms or the release of protons associated with organic anions in manure [37,38], while a lower pH inhibits the ammonia volatilization process [39,40]. Soil ammonium nitrogen (NH_4-N) is a significant factor affecting ammonia volatilization, as NH_4-N can be easily converted to ammonia, part of which is not fixed by the soil and is lost to the atmosphere [41]. This study also found a significant positive correlation between soil mineral nitrogen content and cumulative ammonia volatilization during the tomato reproductive period (Figure 6), suggesting that the accumulation of soil surface mineral nitrogen NH_4-N may trigger ammonia volatilization. The rapid hydrolysis of the nitrogen in urea to NH_4^+ and OH^- by the soil moisture increases the soil NH_4^+ concentration, leading to higher rates of ammonia volatilization [42,43]. In contrast, the conversion of organic nitrogen in manure to NH_4^+-N is slower [44], as the application of organic manure increases the carbon/nitrogen ratio of the soil, leading to a slower mineralization of manure compared to other organic materials. Moreover, the transformation of humus within organic manure, facilitated by microbial processes, can enhance the soil's capacity to adsorb and retain NH_4^+. Consequently, the liquid phase contains reduced NH_4^+ in comparison to soils treated with inorganic fertilizers, leading to a notable decrease in ammonia volatilization losses [45,46]. This may explain the decrease in cumulative ammonia release with the increase in the rate of organic fertilizer substitution observed in this experiment. Studies by Zhang et al. also showed that a 25–50% organic fertilizer substitution does not significantly increase greenhouse gas emissions from paddy fields, but rather slowed down the greenhouse effect [47].

This may be due to the higher nitrogen mineralization capacity of chicken manure, with different types of organic fertilizers having different nitrogen mineralization rates [44]. Compared to cow and sheep manure, chicken manure has a finer texture and smaller carbon-to-nitrogen ratio, resulting in a higher nitrogen mineralization efficiency, which inhibits ammonia volatilization to some extent [48]. In our experiment, the sheep manure treatment exhibited the largest accumulation of ammonia volatilization under the same proportion of organic fertilizer treatment. This may be due to the fact that sheep manure is considered a warm fertilizer, releasing at higher temperatures than cattle manure. With increasing temperature, the proportion of ammonia in the soil's liquid phase increases, and the diffusion coefficient of gas from the liquid phase to the gas phase also increases, facilitating the rapid emission of ammonia. The nitrogen loss due to ammonia volatilization increases as the temperature increases [49].

This study found that drip irrigation with organic fertilizers in combination with chemical fertilizers significantly reduces the volatile accumulation of ammonia, and that this water and fertilizer management strategy is a critical step towards sustainable agriculture. By curbing ammonia emissions, it helps to achieve the mitigation of face source pollution caused by the greenhouse effect. On the other hand, reduced ammonia volatilization has a positive impact on crop yields by minimizing nitrogen losses and improving nutrient efficiency, ensuring a more stable and accessible nitrogen source for plant growth, which increases crop yields and overall productivity.

4.2. Effect of Different Water and Fertilizer Treatments on Soil Mineral Nitrogen

Mineral nitrogen in the soil undergoes migration and morphological transformation during water movement and diffusion, and these processes were explored in this experiment to determine the differences induced by different irrigation techniques. The combination of drip irrigation techniques and organic fertilizer application maintained high mineral nitrogen levels by increasing the water-holding capacity of the soil. At the same time, it led to increased crop yields and reduced the post-harvest mineral nitrogen concentration in the soil, consistent with the results of another study [50]. Compared to surface irrigation, drip irrigation reduced the residual mineral nitrogen concentration and gaseous nitrogen losses (e.g., ammonia volatilization) in the soil, while increasing the crop nitrogen uptake and yield.

The hydrolysis of nitrogen from chemical fertilizers in the soil occurs rapidly and is typically completed within 7–14 days [51]. As a result, mineral nitrogen in the soil treated with chemical fertilizers alone increased rapidly in the short term after fertilization. In contrast, the rate of mineralization of organic nitrogen to the mineral form was controlled by the carbon-to-nitrogen ratio after the application of organic fertilizers [52,53]. The high carbon-to-nitrogen ratio of organic fertilizer input leads to slower nitrogen mineralization and a higher microbial fixation of nitrogen, thus reducing nitrogen loss from fertilizers to some extent [54,55]. The slow release of nitrogen from organic fertilizers provides a long-lasting supply of nitrogen, better meeting the nitrogen demand of vegetable crops [51]. This study also demonstrated that the simultaneous application of organic fertilizers buffered the changes in mineral nitrogen in the soil compared to the application of chemical fertilizers alone. The application of organic fertilizers not only altered the nitrogen transport and redistribution process, but also affected the morphological transformation of nitrogen. Drip irrigation technology combined with organic fertilizer dosing delayed the rise and fall of mineral nitrogen content in the soil, and the time when mineral nitrogen reached its maximum value was also delayed. This delay may be attributed to the inhibitory effect of organic fertilizers on the hydrolysis and nitrification of urea, which aligns with the findings of Yao et al. [24].

In summary, the redistribution of mineral nitrogen in the soil is mainly influenced by water transport and diffusion, which are physical processes mediated by irrigation techniques. Additionally, the interaction of organic fertilizer additions plays a crucial role, including the biochemical processes of nitrogen form transformation. As a result, the morphological transformation of nitrogen to mineral nitrogen is an important factor affecting soil nitrogen transport and redistribution. In order to achieve the efficient and sustainable management of soil fertility nitrogen, it is crucial to consider the interactive effects of organic and chemical fertilizer dosing, as well as drip irrigation techniques, on the morphological transformation of nitrogen to mineral nitrogen. This holistic approach will help to optimize nitrogen utilization and minimize nitrogen losses, ensuring the long-term health and productivity of the soil and crops.

4.3. Optimizing Water and Fertilizer Management to Achieve a Balance between Tomato Yield and Quality

The application of organic fertilizers, either alone or in combination with chemical fertilizers, is increasingly recommended in agricultural production. This practice has been shown to improve fruit yield and quality compared to using chemical fertilizers alone [19,56]. In the present study, the tomatoes treated with organic fertilizer exhibited higher yields, vitamin C contents, and soluble sugar contents, while the titratable acid content was reduced, indicating that organic fertilizers improved the tomato quality while increasing the yield. Similar findings have been reported by Wu et al. [57], who demonstrated that the amalgamation of cattle manure and inorganic fertilizer led to an elevation in tomato yield, along with notable enhancements in the total soluble sugar, vitamin C, and lycopene content. The introduction of organic matter through manure augments the efficiency of soil nutrients and fosters the generation of microbial enzymes, leading to the formation of various simple organic components that contribute to the production of humus [58]. Humus improves the soil structure, stimulates root growth, and further enhances tomato fruit quality [12,57]. Furthermore, organic matter from manure can transport nutrients to deeper soil layers through the soil solution during downward infiltration, benefiting tomato growth in the long term. This is a testament to the positive impact of replacing some chemical fertilizers with organic fertilizers on tomato yield and quality, suggesting that organic fertilizers in combination with nitrogen fertilizer have the potential to improve crop yield and quality in a sustainable manner when put into agricultural production practice. This model has the potential to improve soil health, nutrient availability and overall crop yields in a sustainable manner.

However, heavy applications of manure may lead to reduced soil pH levels, negatively affecting the tomato nutrient uptake and resulting in reduced fruit quality [57], as observed in the CK treatment in this study. The experimental findings revealed a trend in the tomato yield, wherein an initial increase was followed by a subsequent decrease with the rise in the organic fertilizer replacement ratio in the context of the surface irrigation treatment. This might be due to the elevated replacement ratio of organic nitrogen, leading to an initial scarcity of nitrogen assimilated by microorganisms during the early growth stage. Subsequently, there was a limited release of nitrogen in the middle and later stages, which potentially failed to adequately fulfill the crop's nutritional requirements during its advanced growth phase. On the other hand, the increase in the organic fertilizer replacement ratio under drip irrigation and the subsequent increase in yield could be attributed to drip irrigation technology altering the water transport state, accelerating the process of the conversion of organic nitrogen to inorganic nitrogen, and ensuring an adequate supply of nitrogen, which is required for tomato growth. The change in the organic fertilizer replacement ratio showed varying effects on the different qualities of tomatoes, and further research is needed to explore the optimal replacement ratio to achieve a balance between different quality aspects.

Most studies have indicated that drip irrigation fertilization can increase tomato yield and quality [50,59,60]. The nutrient content in tomato fruits is significantly influenced by yield, which is in line with the findings of studies on lentils, fodder, leafy vegetables, and wheat [61–65]. However, it is worth noting that in this experiment, although drip irrigation increased the yield, it also led to a reduction in the tomatoes' soluble sugar content, similar to the findings of Xing et al. [66]. This reduction is attributed to drip irrigation reducing the soil surface evaporation, resulting in a more uniform distribution of water in the soil, an increased plant uptake and utilization of nutrients, and a diluting effect on nutrient concentrations. Thus, yield and quality are interconnected and may constrain each other. However, the negative effects of drip irrigation on quality can be mitigated to some extent through the targeted application of organic fertilizers in combination with drip irrigation technology, achieving a balance between yield and nutritional quality. Further research is needed to optimize the application of organic fertilizers to achieve this balance.

5. Conclusions

Drip irrigation with organic fertilizer significantly reduced ammonia volatilization by 42.09–80.81% compared to conventional surface irrigation with urea (CK). Increasing the proportion of organic fertilizer further reduced ammonia volatilization by 0.05–0.54%.

The mineral nitrogen content increased by 1097.84% and 325.17% with surface irrigation and drip irrigation, respectively, during the reproductive period. However, higher replacements of organic fertilizer in drip irrigation (the SDIFC2, SDIFC1, and SDIFC3 treatments) resulted in a reduction in mineral N in the 0–10 cm soil layer.

The highest tomato yield of 13,414 kg/hm^{-2} was obtained with the SDIFC3 drip irrigation strategy, which was 27.31% higher than CK. The strategy also increased the vitamin C and soluble sugar contents by 45.74% and 31.17%, respectively, while the titratable acid content decreased by 49.38%.

Our experiments identified the ideal organic fertilizer strategy for greenhouse tomato cultivation as being SDIFC3 (50% chicken manure organic fertilizer and 50% urea). This strategy effectively minimized ammonia volatilization under drip irrigation while enhancing tomato yield and quality through a synergistic effect.

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