Article

Characteristics and Driving Factors of Nitrogen-Use Efficiency in Chinese Greenhouse Tomato Cultivation

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Abstract: Excessive nitrogen fertilizer application in greenhouses could cause a significant variation in the nitrogen-use efficiency at the regional scale. This study aims to quantify agronomic nitrogen-use efficiency (AE_N) and identify its driving factors across Chinese greenhouse tomato cultivation. Three hundred and forty-eight AE_N values were obtained from 64 papers, including mineral nitrogen (MN) and mineral combined with organic nitrogen (MON) treatments. The average AE_N values for the MN and MON treatments were $56.6 \pm 7.0 \text{ kg kg}^{-1}$ and $34.6 \pm 3.5 \text{ kg kg}^{-1}$, respectively. The AE_N of the MN treatment was higher than that of the MON treatment for cultivation using soil with an organic matter content of less than 10 g kg^{-1} and the drip fertigation method. The AE_N s of the MN and MON treatments were divided into two segments according to the nitrogen application rate. The inflection points of the nitrogen application rate were 290 and $1100 \text{ kg N ha}^{-1}$ for the MN and MON treatments, respectively. When the ratio of organic nitrogen to total nitrogen was less than 0.4, it was beneficial for improving the AE_N . The soil organic matter content and the nitrogen application rate were the most critical factors determining the AE_N . These results suggest that rationally reducing the nitrogen input and partially substituting mineral nitrogen with organic nitrogen can help improve the nitrogen-use efficiency.

Keywords: greenhouse tomato; management practices; soil properties; agronomic nitrogen-use efficiency

Citation: Ren, T.; Li, Y.; Miao, T.; Hassan, W.; Zhang, J.; Wan, Y.; Cai, A. Characteristics and Driving Factors of Nitrogen-Use Efficiency in Chinese Greenhouse Tomato Cultivation. *Sustainability* **2022**, *14*, 805. <https://doi.org/10.3390/su14020805>

Academic Editor: Mohammad Aslam Khan Khalil

Received: 29 November 2021

Accepted: 29 December 2021

Published: 12 January 2022

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1. Introduction

The global demand for vegetable production is booming with the improvement of human living standards [1]. As the world's primary vegetable, the tomato is becoming increasingly popular because of its high concentration of vitamins, lycopene, minerals, antioxidants, and other nutrients [2,3]. Chinese tomato production is the largest globally, accounting for 33.82% of the global tomato production [4]. Tomato production in China increased from 50.7 million tons in 2013 to 61.6 million tons in 2018, and more than half of this tomato production came from greenhouse cultivation [4]. Nitrogen, as an essential nutrient, is vital for crops to grow, especially in greenhouse tomato cultivation. Aiming to obtain a high tomato yield, excessive mineral nitrogen fertilizer has been applied in greenhouse tomato production [5,6]. Based on the data of these papers published from 1965 to 2019, the average mineral nitrogen application rate was 656 kg N ha^{-1} , which was above the rate to meet the tomato demand and led to more reactive nitrogen loss, a higher environmental cost, and a lower nitrogen-use efficiency [7]. As a result, strictly controlling the overuse of mineral nitrogen fertilizer is essential to decrease environmental pollution and increase nitrogen utilization. At present, the Chinese Government has proposed an accurate nutrition management framework to achieve the goal of zero growth in fertilizer use [8]. This could guide farmers to replace mineral nitrogen fertilizer with an organic fertilizer in the farming system, especially for greenhouse vegetable production [9]. The application of organic fertilizers, such as animal manure and straw residue, could promote

the nutrient recycling of agricultural resources, improve soil fertility, and increase vegetable yield [10]. China is the global largest greenhouse tomato producer, with a planting area of one million hectares, of which 42% is used for open-air cultivation and 35% is used for greenhouse cultivation, and abundant manure and straw resources [4]. Therefore, clarifying how to rationally manage nitrogen nutrition in greenhouses, including mineral and organic fertilizers, is crucial.

Mineral nitrogen, i.e., ammonium and nitrate nitrogen, can be easily absorbed by vegetables [11]. The application of mineral nitrogen usually results in a quicker reaction compared with organic nitrogen. Organic nitrogen is first degraded into mineral nitrogen, which can then be taken up by vegetables. When mineral nitrogen is combined or substituted with organic nitrogen, the corresponding yield and nitrogen-use efficiency remains uncertain. Inconsistent results have been reported based on field experiments. Compared with mineral nitrogen applied alone, the combined application of mineral nitrogen and organic nitrogen increased [12] or decreased [13] the nitrogen-use efficiency, or no significant differences [14] were observed. These variations could be attributed to different farming systems, climate conditions, irrigation, and fertilization practices. On the other hand, greenhouse tomato cultivation is semiclosed and is quite different to open-air cultivation. The atmospheric environment inside the greenhouse is relatively stable. Hence, the nitrogen-use efficiency in greenhouse cultivation mainly depends on the management practices (fertilizer types, nitrogen application rate, and top-dressing method) [15] and the soil properties (soil types, soil pH, soil total nitrogen content, and soil organic matter) [14]. At present, for greenhouse tomato cultivation, little is known about the responses and trends of the tomato yield and nitrogen-use efficiency under different management practices and soil properties at the regional scale. Moreover, changes in the ratio of organic nitrogen to total nitrogen can also affect the tomato yield and nitrogen-use efficiency. Previous studies have shown that a moderate substitution ratio of organic nitrogen to total nitrogen can increase the nitrogen-use efficiency without reducing the yield in wheat–summer maize rotation [16]. Still, a high ratio of organic nitrogen to total nitrogen can decrease the nitrogen-use efficiency and yield [17]. Whether there is a similar trend in greenhouse tomato cultivation needs further clarification.

China has taken into account the effects of the combined application of mineral and organic nitrogen in the sustainable production of greenhouse tomatoes. Currently, there have been several comprehensive reports on the effects of different nitrogen fertilizer forms on tomato production [18], tomato quality [19], and nitrous oxide emissions and nitrogen leaching [20]. However, the nitrogen-use efficiency of different nitrogen fertilizer forms has not been reported on at the regional scale. By reviewing and integrating the results of published articles based on greenhouse tomato cultivation, the overall objectives of this study are: (1) to comprehensively assess the effects of mineral nitrogen applied alone (MN) and combined with organic nitrogen (MON) on nitrogen-use efficiency, and (2) to identify the driving factors determining nitrogen-use efficiency in the greenhouse tomato cultivation of China. The results of this study could fill the gaps in our knowledge about the responses of nitrogen application in greenhouses to the combined application of mineral and organic fertilizer at the national scale. It may serve as a guide for greenhouse tomato farmers to rationally manage mineral and organic nitrogen nutrition.

2. Materials and Methods

2.1. Database Collection, Definitions, and Calculation

To establish a comprehensive database of the application of different nitrogen forms across Chinese greenhouse tomato production, strict criteria (described below) were adopted to obtain the relevant experimental data from the literature published before and during March 2020 through Web of Science (<http://apps.webofknowledge.com>, accessed on 20 March 2020), Google Scholar (<https://scholar.google.com>, accessed on 20 March 2020), and China Knowledge Resource Integrated Database (<http://www.cnki.net/>, 20 March 2020). Keywords included “China”, “greenhouse”, “tomato”, “nitrogen”, and “yield”. The

selected data needed to meet the following requirements: (a) the experiments were carried out under greenhouse conditions, and laboratory and pot experiments were excluded; (b) the experimental variety was ordinary tomato, excluding cherry tomato; (c) information about nitrogen application and tomato yield was reported; and (d) if the experimental data in the target literature were presented in the form of tables or text, we could directly obtain the experimental data. For figures, the software of GetData Graph Digitizer 2.24 was used to obtain these data indirectly.

Nitrogen fertilizer forms were divided into MN and MON to explore their effects on tomato production and nitrogen-use efficiency in the greenhouse. The substitution ratios of nitrogen application by organic fertilizer were calculated simultaneously. The nitrogen fertilizer application rate was converted into pure nitrogen. If pure nitrogen was shown in the literature, it was directly recorded in our database. If only the content was specified, the pure nitrogen amount was obtained by statistical calculation. If the nitrogen content of the organic fertilizer was not provided, the organic nitrogen content could be calculated according to “China Organic Fertilizer Nutrition” [21]. For organic nitrogen types, the most significant contributor came from the manure of poultry (51%) and livestock (21%), followed by commercial organic fertilizer (23%), straw, and biogas residue (5%).

Different management practices and soil properties were also extracted and clarified from the targeted literature, including fertilizer types (urea, slow controlled-release fertilizer, diammonium phosphate, water-soluble fertilizer), top-dressing methods (fertilization with flooding water, drip fertigation, furrow irrigation with fertilization), and soil physicochemical properties (soil types and texture, soil organic matter, soil total and available nitrogen, soil total and available phosphorus, and soil pH). Complex natural environments, diverse climate types, and a high intensity of human activities lead to the uniqueness of Chinese soil. The main soil types in China can be summarized as red soil, brown soil, black soil, chestnut soil, desert soil, tidal soil, irrigation and silt soil, paddy soil, saline–alkaline soil, and so on. To be consistent with international soil classification, soil types in our study were divided into anthrosols (hortisols, rigisols, and paddy soil), arenosols, cambisols, gleysols, and solonchaks, according to the FAO classification [22]. Soil organic matter was divided into three categories: $<10 \text{ g kg}^{-1}$, $10\text{--}20 \text{ g kg}^{-1}$, and $>20 \text{ g kg}^{-1}$. Soil pH was divided into acidic soil (<6.5), neutral soil ($6.5\text{--}7.5$), and alkaline soil (>7.5) (Tables S1 and S2).

Nitrogen agronomic efficiency (AEN) reflected the yield production per unit amount of nitrogen fertilizer and unit area. It was calculated via the following equation [18]:

$$AE_N = (Y - Y_0) / F \quad (1)$$

where Y and Y_0 (10^3 kg ha^{-1}) are the tomato yields with nitrogen fertilization and without fertilization, respectively, and F (kg ha^{-1}) represents the total amount of nitrogen applied.

The relative output value was used to assess the relationship between yield earning and fertilizer cost. It was calculated via the following equation:

$$\text{Output value} = (\text{tomato price} \times \text{tomato yield}) - (\text{N fertilizer price} \times \text{amount of N fertilizer}) \quad (2)$$

The average price of tomatoes was 0.72 USD kg^{-1} . The average prices of urea, slow controlled-release fertilizer, diammonium phosphate, water-soluble fertilizer, and organic fertilizer were 0.29, 0.65, 0.35, 0.32, 1.61, and 0.10 USD kg^{-1} , respectively. All prices were obtained from the Chinese food information network (<http://www.grain.gov.cn/Grain/Wheat.aspx>, 25 June 2020) and China’s fertilizer network (<http://www.fert.cn/>, 25 June 2020).

In total, we collected 348 paired data entries from 64 published papers. The experimental sites spanned from 27.8° N (Ruian) to 45.8° N (Haerbin) in geographic latitude and from 98.7° E (Jiuquan) to 126.7° E (Haerbin) in geographic longitude (Figure 1). For MN, 41 studies were conducted with 200 paired data, and MON was included in 32 studies with

148 paired data (Table S2). To ensure the accuracy of results, variables with a sample size of less than five were not shown in the figures or tables.

Figure 1. The distribution of 121 experimental sites from 64 published papers. Letters MN (50 experimental sites) and MON (41 experimental sites) represent mineral nitrogen applied alone and mineral combined with organic nitrogen, respectively.

2.2. Statistical Analysis

The distribution of 121 experimental sites is shown in Figure 1, using ArcMap10.5. A linear regression equation was used to fit the relationship between AE_N and longitude under MN and MON treatments. The difference in AE_N between MN and MON treatments under different management practices and soil properties was analyzed by one-way ANOVA. An LSD test and an independent sample *t*-test were conducted using SPSS 20.0. The relationships between AE_N and output value and nitrogen fertilizer application rate were examined by the quadratic polynomial regression using SigmaPlot 10.0. To explore the relative influence of management practices and soil properties in controlling the variation of AE_N , based on theoretical knowledge and the validity of our dataset, a total of 11 variables (soil type and texture, soil organic matter, soil total and available nitrogen, soil total and available phosphorus, soil pH, nitrogen application rate, fertilizer types, and top-dressing methods) were first input into a boosted regression tree model to select the driving factors. Six variables (nitrogen application rate, soil organic matter, top-dressing methods, soil pH, soil types, and fertilizer types) were retained according to their effects on predictive performance. The boosted regression tree model adopted the recommended parameter values: learning rate (0.01), bag fraction (0.50), cross-validation (10), and tree complexity (5) [23,24]. The Bernoulli method was used for the boosted regression tree analysis because of the categorical variables [23,24]. The boosted regression tree model was constructed using the gbm package in R, version 3.3.3 [24].

3. Results

3.1. Spatial Distribution

The AE_N under the MN and MON treatments showed a significant negative linear relationship with the longitude ($p < 0.01$) (Figure 2). The average AE_N under the MN treatment was $56.6 \pm 7.0 \text{ kg kg}^{-1}$, which was higher than for the MON treatment ($34.6 \pm 3.5 \text{ kg kg}^{-1}$)

(Figure 3). The MON treatment decreased the AE_N by 38.9% compared with the MN treatment.

Figure 2. Geographic longitude patterns of agronomic efficiency of applied nitrogen ($kg\ kg^{-1}$) when mineral nitrogen is applied alone (a) and when mineral combined with organic nitrogen (b) treatment is applied.

Figure 3. The agronomic efficiency of applied nitrogen ($kg\ kg^{-1}$) when mineral nitrogen is applied alone (MN) and when mineral combined with organic nitrogen (MON) is applied for fertilizer types (a,b) and top-dressing methods (c,d). Notes: fertilizer types included urea, slow controlled-release fertilizer (SCF), and diammonium phosphate (urea + DP); different top-dressing methods included fertilization with flooding water (FFW), drip fertigation (DF), and fertilization with furrow irrigation (FIF). Different letters denote significant differences at the $p < 0.05$ level.

3.2. Management Practices

For the fertilizer types, there was no significant difference between the urea and the slow controlled-release fertilizer for the AE_N under the MN treatment, with 45.5 and 48.3 kg kg^{-1} (Figure 3a), respectively. The AE_N of the urea fertilizer used with the MON treatment (39.8 kg kg^{-1}) was higher than that of the urea and diammonium phosphate fertilizer (18.6 kg kg^{-1}) (Figure 3b). For the top-dressing methods, the AE_N of drip fertigation used with the MN treatment (153.6 kg kg^{-1}) was significantly higher than that of furrow irrigation with fertilization (20.3 kg kg^{-1}) and fertilization with flooding water (18.4 kg kg^{-1}) (Figure 3c). The AE_N s of drip fertigation and furrow irrigation with fertilization (56.3 and 54.9 kg kg^{-1} , respectively) used alongside the MON treatment were higher than those of fertilization with flooding water (23.7 kg kg^{-1}) (Figure 3d).

The AE_N s of the MN and MON treatments were divided into two segments according to the nitrogen application rates (Figure 4). The inflection points of the nitrogen application rate were 290 and 1100 kg ha^{-1} for the MN and MON treatments, respectively. Before the inflection points, the AE_N s of the MN and MON treatments decreased rapidly, with slopes of 675.03 and 30.16, respectively. After the inflection points, the AE_N s of the MN and MON treatments showed a slight decrease, with slopes of 18.79 and 2.35, respectively. The output values were also divided into two segments that exhibited negative trends. The maximum output values under the MN and MON treatments were 0.75×10^5 and 0.79×10^5 USD ha^{-1} , respectively. The MON treatment increased the nitrogen input by 85.9% in the greenhouse tomatoes. A high ratio of organic nitrogen to total nitrogen resulted in a low AE_N . When the percentage of organic nitrogen to total nitrogen was less than 40, it was beneficial for improving the AE_N (Figure 5).

Figure 4. The relationship between nitrogen application rate (10^3 kg ha^{-1}) and agronomic efficiency of applied nitrogen (kg kg^{-1}) and relative output value ($\text{USD} \times 10^5 \text{ ha}^{-1}$) under mineral nitrogen treatment (a,c) and mineral combined with organic nitrogen treatment (b,d). ****** means significant correlation at the $p < 0.01$ level.

Figure 5. The effect of different ratios of organic nitrogen to total nitrogen (%) on agronomic efficiency of applied nitrogen (kg kg⁻¹). Different letters denote significant differences at the $p < 0.05$ level.

3.3. Soil Properties

For the soil types, the AE_N in the arenosols (153.3 kg kg⁻¹) and solonchaks (153.3 kg kg⁻¹) under the MN treatment was significantly higher than in the anthrosols, cambisols, and gleysols (67.5, 21.1, and 33.0 kg kg⁻¹, Figure 6a). Higher AE_N s under the MON treatment were found in the anthrosols (46.5 kg kg⁻¹) and gleysols (40.2 kg kg⁻¹) compared with the cambisols (Figure 6b). For the MN treatment, the AE_N in soils with low levels of organic matter (<10 g kg⁻¹) was significantly higher than in soils with high levels of organic matter (>10 g kg⁻¹). The AE_N under the MN treatment showed an increasing trend with the soil pH. The AE_N under the MON treatment showed no significant difference according to the different levels of organic matter content in the soil, the soil pH, and the soil total nitrogen content (Figure 6b,f,h).

3.4. Driving Factors

The AE_N under the MN and MON treatments was driven by the management practices and soil properties (Figure 7). The level of organic matter in the soil, nitrogen application rate, top-dressing methods, soil pH, soil types, and fertilizer types accounted for 50.3%, 22.4%, 13.1%, 8.8%, 3.5%, and 1.9% of the AE_N variations under the MN treatment, respectively, and for 34.7%, 29.4%, 17.8%, 10.9%, 4%, and 3.2% of the AE_N variations under the MON treatment, respectively. The levels of organic matter in the soil and the nitrogen application rate were the most influential variables on the AE_N among the six selected variables. Overall, the boosted regression tree model could explain 92% and 86% of the AE_N variance under the MN and MON treatments, respectively.

Figure 6. The agronomic efficiency of applied nitrogen (kg kg^{-1}) under mineral nitrogen treatment (MN) and mineral combined with organic nitrogen treatment (MON) for different soil types (a,b), levels of organic matter in the soil (g kg^{-1} ; (c,d)), soil pH (e,f), and soil total nitrogen (g kg^{-1} ; (g,h)). Note: different letters denote significant differences at the $p < 0.05$ level.

Figure 7. The relative influence (%) of predictor variables for the boosted regression tree model of agronomic efficiency of applied nitrogen (AE_N , kg kg^{-1}) under mineral nitrogen treatment (a) and mineral combined with organic nitrogen treatment (c). The observed agronomic efficiency of applied nitrogen (kg kg^{-1}) and those predicted by the boosted regression tree model using various predictors are shown in (b,d). Note: predictor variables included management measures (nitrogen application rate, top-dressing methods, and fertilizer types) and soil properties (levels of organic matter in the soil, soil pH, and soil types).

4. Discussion

In recent years, a large quantity of mineral nitrogen fertilizer has been used in greenhouse vegetable cultivation in China, which has contributed to yield improvement [5]. However, it has also caused high losses of reactive nitrogen from the environment, which has increased the risk of soil degradation and pollution [25]. The application of organic fertilization for vegetables is a time-honored practice and widely accepted by farmers in China. Previous studies have indicated that the combined application of mineral and organic fertilizer could improve the soil's physical, mineral, and biological properties and have benefits for the vegetable yield and quality improvement [26]. Our integrated analysis showed that the MON treatment increased the yield by 16.2% but decreased the AE_N by 38.9% compared with the MN treatment (Figure S1). From the results of the global meta-analysis, the nitrogen-use efficiency of mineral nitrogen fertilizer applied alone in greenhouse vegetables was 61.1% higher than that of mineral combined with organic nitrogen fertilizer [27]. Moreover, the AE_N gradually reduced with the ratio of organic nitrogen to total nitrogen from 20% to above 60%. Vegetables cannot directly use organic nitrogen unless microorganism decomposition occurs, that is, mineralization [28]. Correspondingly, unlike the quicker reactions of nitrogen from mineral fertilizer, organic nitrogen may present a hysteretic supply of the available nitrogen and result in a lower nitrogen-use efficiency [13]. For the MN and MON treatments, the average nitrogen application rates were 434 kg ha^{-1} and 807 kg ha^{-1} , respectively (Figure S1). Thus, a high nitrogen input could cause a low AE_N , especially for the MON treatment.

A recent meta-analysis indicated that the partial substitution of mineral nitrogen for organic nitrogen increased upland crop yield and nitrogen-use efficiency, which was not inconsistent with our results regarding greenhouse tomato production [29]. The nitrogen demand for upland crops is smaller than for vegetables in the greenhouse. Organic fertil-

izers provide the slow release of nitrogen by mineralization as an additional source and improve soil structure and microorganism activity, which benefits crop growth, especially at reproductive stages [30]. For tomatoes in greenhouses, the biomass is much larger than for most crops. Thus, the demand for nitrogen is immense at the vegetative stage. Organic fertilizer may not provide sufficient nitrogen for the initial stage of tomatoes because of its slow-release effect. Hence, a high ratio of organic nitrogen to total nitrogen caused a low AE_N in our study. The complete substitution of mineral nitrogen for organic nitrogen significantly decreased the crop nitrogen-use efficiency by 20.5% [31]. Xia also showed that the crop yield and nitrogen-use efficiency would decrease when the ratio of organic nitrogen to total nitrogen was above 75% [32]. The substitution of 25% of the recommended fertilizer dose was possible when a higher amount of organic manure and biofertilizer were combined together in tomato cultivation in India [33]. All these results suggest that when the ratio of organic nitrogen to total nitrogen is much higher than 50%, the hysteretic supply of nitrogen affects plants' nitrogen-use efficiency and yield output. Hence, although organic fertilizer has many advantages in improving soil fertility, it is important to balance the ratio of mineral nitrogen to organic nitrogen reasonably to provide enough nutrition, thus increasing the nitrogen-use efficiency. Based on the results of our study, a high percentage of organic nitrogen to total nitrogen is not recommended in greenhouse tomato cultivation.

Understanding the driving factors controlling nitrogen-use efficiency is necessary for developing effective fertilizer strategies in greenhouse tomato cultivation. Our boosted regression tree analysis results showed that organic matter content of the soil was the most influential variable determining the AE_N , accounting for 50.3% and 34.7% of the variation under the MN and MON treatments, respectively. The organic matter content of the soil plays a vital role in maintaining soil fertility and improving soil structure, and thus helps to increase nitrogen-use efficiency [34]. A study into the conservation agriculture and integrated soil fertility management of Kenya showed that the low-fertility fields had a significantly lower agronomic use efficiency compared to the high-fertility fields [35]. As the combined application of organic fertilizer could replenish organic matter in soil, the relative influence of organic matter was lower in the MON treatment than in the MN treatment. On the other hand, the spatial variability of the AE_N indicated that the nitrogen-use efficiency decreased with an increased longitude in China. This could be attributed to the low organic matter content of the soil and the poor soil quality. With an increased longitude, the climate becomes dry. The soil water content also decreases in West China, limiting plant nitrogen uptake [36]. Additionally, soil organic matter enhances the immobilization of external nitrogen by soil microorganisms and clay minerals, consequently reducing leaching loss and improving nitrogen-use efficiency [37]. It is suggested that the application of organic fertilizer should be increased when soil organic matter content is limited, especially in West China.

The nitrogen application rate was another critical factor affecting tomato nitrogen-use efficiency. The AE_N of the MON treatment decreased slowly and smoothly with the nitrogen application rate, while the AE_N of the MN treatment decreased sharply. This might be due to the slow release of nitrogen from organic fertilizer [28]. Excessive nitrogen application was found in 52 studies (accounting for 14.9% of all studies), giving negative values of AE_N . In these cases, the available nitrogen in the soil was rich and sufficient for tomato growth due to the abundant residual nitrogen from preceding vegetable cultivation. Further application of nitrogen fertilizer had little benefit to yield improvement. According to research conducted in Florida, tomato production systems showed that increasing the rate of nitrogen fertilizer did not result in benefits to fruit and/or shoot biomass nor to N accumulation, but substantially increased NO_3 -N leaching [38]. Even worse, excessive nitrogen might cause nutrient stress, thus inhibiting plant growth and leading to a series of environmental pollutions [39]. The relative output value increased and reached a peak value when more nitrogen was applied. Rationally determining the nitrogen rate should balance the nitrogen-use efficiency, cost, and benefits. The fitted curves of the AE_N and the relative output value in our study suggested that: (1) nitrogen application was sufficient in

Chinese greenhouse tomato cultivation, and the tremendous nitrogen application rate was the main reason behind the low nitrogen-use efficiency, especially for mineral combined with organic nitrogen fertilizer; and (2) excessive nitrogen could not achieve high output values because of the high input, and the inflection point might be used as a reference for designing a nitrogen application rate guideline.

Different top-dressing methods significantly affected the nitrogen-use efficiency by changing the synergistic role of water and fertilizer in crop growth [40]. Traditional fertilization with flooding water reduced the soil temperature and increased the air humidity in greenhouses, increasing the risk of low water- and nitrogen-use efficiency [41]. This was the reason for the low AE_N of the top-dressing method of fertilization with flooding water for both the MN and MON treatments. Top-dressing with furrow irrigation showed a higher AE_N and saved water compared with flooding irrigation. However, furrow irrigation and flooding irrigation could cause a considerable nitrogen loss by leaching, as nitrogen nutrients ran off along with the water flow [42]. Sánchez-Martín also reported that drip irrigation is a method that can be used to save water and mitigate the emission of the atmospheric pollutants NO and N_2O in Spanish horticultural crops [43]. Drip fertigation is an advanced top-dressing method that could significantly reduce the input of nitrogen fertilizer and water in greenhouse cultivation [44] and presented the highest AE_N in our study. Drip irrigation precisely controls the quantity and timing of fertilizer and irrigation application to positively influence soil microorganisms and root activity, thus promoting nitrogen- and water-use efficiency.

Other factors, such as the soil pH, soil types, and fertilizer types, also impacted the nitrogen-use efficiency. A decrease in the soil pH leads to soil acidification, reduces soil microorganism and enzyme activity, and affects the vegetable rhizosphere, decreasing the AE_N by controlling nitrogen absorption [45]. Additionally, the AE_N under the MN treatment was lower compared with the MON treatment in soil with a $pH < 6.5$. Organic fertilizer application improved the soil buffering capacity and maintained a stable soil pH [46]. This was why there were no significant differences in the AE_N under the MON treatment between acidic soil, neutral soil, and alkaline soil. Vegetables can directly absorb and utilize the fast-reacting nitrogen from mineral fertilizer in most soils. The anthrosol soil type enhances the retention of organic matter in soil due to its high clay content, which becomes a primary source of the nutrients released under conditions of insufficient organic matter during cultivation [47]. Therefore, the AE_N under the MN treatment was higher than under the MON for different soil types. Controlled-release fertilizer can meet plants' nitrogen requirements according to their growth characteristics and cause lower nitrogen losses and environmental costs [48]. However, the price of controlled-release fertilizer is relatively high, which is a significant challenge for popularizing its use in Chinese greenhouses. A key issue is that the risk of profit loss must be small and, in many cases, that the profit increase must be substantial to make the technology attractive for a farmer.

5. Conclusions

This timely study identified the importance of field practices and soil properties in improving nitrogen-use efficiency. It can provide references and suggestions for managing mineral and organic nitrogen rationally in greenhouse tomatoes. The mineral nitrogen rate should be reduced, and the reduction percent can be judged according to the conditions of the residual nutrients in the soils of the greenhouse. Organic nitrogen can be used as a substitute for the decreased amount of mineral nitrogen. Especially for the low-carbon-content soil in West China, increasing the rate and ratio of organic fertilizer is recommended. Moreover, drip fertigation and controlled-release fertilization are considerably beneficial practices when integrated with decreased nitrogen input, further improving tomato yield and nitrogen-use efficiency in greenhouses. Our results emphasize that reasonable measures can be taken to reduce nitrogen input, increase nitrogen-use efficiency, and improve farmers' income according to the specific situation.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/su14020805/s1>, Table S1: summary of site characteristics, soil pH, and soil organic matter (g kg^{-1}) under mineral nitrogen applied alone and mineral combined with organic nitrogen treatments across Chinese greenhouse tomato cultivation; Table S2: the value of nitrogen agronomic use efficiency (kg kg^{-1}) under different management practices and soil properties and the summary of nitrogen application rate (kg ha^{-1}), tomato yield (t ha^{-1}), output value (USD ha^{-1}) for mineral nitrogen applied alone and mineral combined with organic nitrogen treatments. Notes: fertilizer types included urea, slowly controlled release fertilizer (SCF), and diammonium phosphate (Urea+DP); different top dressing methods included fertilization with flooding water (FFW), drip fertigation (DF) and fertilization with furrow irrigation (FIF); Figure S1: the yield (Mg ha^{-1} , a) and nitrogen application rate (kg kg^{-1} , b) under mineral nitrogen applied alone (MN) and mineral combined with organic nitrogen (MON).

Author Contributions: Conceptualization, T.R., Y.L. and A.C.; Data curation, T.R., T.M. and J.Z.; Investigation, Y.L., W.H. and Y.W.; Methodology, T.R. and A.C.; Resources, Y.L.; Supervision, Y.L.; Writing—original draft, T.R. and A.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by National Natural Science Foundation of China (42007073), Chinese State Key Special Program on Severe Air Pollution Mitigation (Grant No. DQGG0208) and the National Key Research and Development Program (Grant No. 2018YFC0213300). We thank the authors whose data and work was included in our dataset.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

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