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Improving the Yield and Quality of Tomato by Using Organic Fertilizer and Silicon Compared to Reducing Chemical Nitrogen Fertilization

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Abstract: Essential macronutrient nitrogen (N) is crucial for plant growth and yield, but excessive chemical N fertilizer not only increases unnecessary production costs but also causes environmental pollution. Therefore, reducing N fertilizer use by increasing organic fertilizer use is crucial for sustainable agriculture. In this study, we investigated the effects of three nitrogen levels—the recommended rate (N), a 20.0% reduced rate (0.8N), and a 40.0% reduced rate (0.6N)—and two levels of organic fertilizer—a normal dose (M) and a four-times the normal dose (4M)—combined with root application of the beneficial element silicon (Si) on the photosynthetic characteristics, yield, and fruit quality of the tomato cultivar 'Tianxi No. 5'. Compared with M + N treatment, the longitudinal diameter, transverse diameter, fruit weight, and fruit yield of tomato fruit in 4M + 0.6N treatment significantly increased by 12.4%, 14.6%, 14.5%, and 12.8%, respectively, while the yield was further improved with Si application. In addition, a reduction in N fertilizer and an increase in organic fertilizer, combined with Si application, improved fruit quality parameters such as concentrations of vitamin C, lycopene, phenols, flavonoids, sucrose, fructose, etc., and promoted sugar metabolism-related enzyme activity (sucrose synthase, invertase, and sucrose phosphate synthase) and the accumulation of N in the fruit. The principal component analysis and three-factor analysis of variance (ANOVA) of the fruit quality and yield indices showed that nitrogen fertilizer, organic fertilizer, silicon fertilizer, and the interaction of the three had significant effects on the quality and yield of tomato fruits, and that the 4M + 0.6N + Si treatment had the best combined effect on the yield and quality of the tomatoes. Thus, a moderate reduction in chemical N fertilizer, combined with increased organic fertilizer and Si, could be an effective agronomic practice for improving the yield and quality of tomatoes.

Keywords: organic fertilizer; mineral N fertilizer; fruit quality; silicon fertilizer; tomato

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1. Introduction

Tomato (*Solanum lycopersicum* L.) is a popular vegetable crop because of its sweet, sour, juicy, and nutritious properties [1]. The economic and nutritional significance of tomatoes is underscored by their rich content of vitamins, minerals, and antioxidants, which contribute to a balanced diet and overall health. As an annual or perennial vegetable crop, tomatoes meet the growing needs of consumers and industries. However, their cultivation often requires a significant amount of nitrogen (N), a crucial macronutrient for plant growth and yield [2,3]. When crop demand increases, the optimal number and rate of top dressing could improve N availability [2]. However, the excessive use of chemical N fertilizers not only escalates production costs but also contributes to environmental pollution [4,5]. Therefore, the pursuit of sustainable agriculture necessitates a reduction in N fertilizer use and an increase in organic fertilizer.

In plants, N largely determines biomass growth [3]. Nitrogen is also involved in the synthesis of chlorophyll, amino acids, and proteins in plants, which directly participate in the photosynthetic process [6,7]. Nitrogen has a strong correlation with the carboxylation capacity and electron transfer rate in plant photosynthesis, and an appropriate N dose can help enhance enzyme activity and chlorophyll content in plant leaves, thus improving plant photosynthesis [8].

Plants adopt two primary strategies to obtain soil nutrients. Firstly, plants directly absorb nutrients from the soil through their roots, a process known as the direct nutrient absorption pathway. Secondly, plants form symbiotic relationships with microbes to efficiently obtain nutrients from the environment, a method termed the indirect nutrient absorption pathway [9,10]. Although N is abundant in nature, most of it cannot be directly utilized by plants. Therefore, plants must rely on other N-containing substances in the environment to meet their growth and developmental needs [11]. Soil N is the primary source of N supply in plants. Consequently, low N content in soil limits plant growth and affects crop yield and quality [12,13]. To achieve better economic benefits, Chinese vegetable farmers typically apply large quantities of chemical fertilizers, such as N fertilizers, during vegetable production. Therefore, studying N fertilizer reduction technology is of great significance.

The combined application of organic and chemical fertilizers is a significant means to maintain the sustainable utilization of soil fertility, and also an important production tool to optimize agricultural yield. Such fertilization reduces the application of chemical fertilizer and protects the environment [14,15]. The demand for fertilizer has increased significantly, in order to obtain higher yields and maintain high-intensity vegetable production. To regulate this high demand for chemical fertilizers, alternative technologies/practices like organic fertilizer are constantly being tested by researchers. The application of organic fertilizer improves the quality and yield of crops by improving photosynthetic efficiency and thereby increasing biomass [16]. Adekiya et al. [17] showed that organic fertilizer combined with N, phosphorus (P), and potassium (K) fertilizer improved the plant growth, yield, and contents of minerals, proteins, carbohydrates, and mucilage in *Abelmoschus esculentus*. Recent studies have shown that the long-term application of organic fertilizer promises a continuous improvement in soil productivity and crop yield in China [18]. Therefore, combining organic fertilizer and chemical fertilizer is of great significance to improve crop quality and yield.

Silicon (Si) is the second most abundant element in the earth's crust. It is frequently absorbed in large quantities by crops without causing toxicity [19]. Although Si is not an essential nutrient element for plant growth, its application is beneficial to plant growth and can also improve crop yield. Moreover, Si application could alleviate the effects of various stresses on plants, such as those induced by salt, low temperature, and nutrient deficiency [20,21]. As Si can enhance plant growth under low nutrient status, it can potentially be applied in fertilizer reduction strategies for greenhouse vegetables [22]. Foliar spraying of Si fertilizer can significantly improve the firmness of tomato fruit, providing an effective measure to delay the aging of tomato fruit and subsequently improving its storage and transportation [23]. Other studies have shown that exogenous Si can meaningfully promote the growth and development of the root system, chlorophyll content, relative leaf water content, gas exchange, and P and K absorption in roots and fruits. It can also increase quality indices such as fruit hardness and lycopene in tomato. In addition, supplementation of Si to the nutrient solution significantly increased the Si content in the roots, stems, leaves, and fruits of tomato plants, with the Si content further elevating in all organs with increasing plant growth [24,25]. The results of Udalova et al. [26] showed that treatment with 0.5 and 1.0 μg/mL nano-Si solution could promote the increases in photosynthetic pigments and the contents of phosphorus (P), magnesium (Mg), potassium (K), selenium (Se), and iron

(Fe) in the leaves of the tomato plant. Hoffmann et al. [27] demonstrated that exogenous Si can boost plant vitality and improve vegetative growth and fruit yield by regulating physiological parameters, thereby protecting plants from biotic stress.

For tomato crops, the application of nitrogenous fertilizers plays a significant role in both the morphological growth and photosynthetic processes of tomato plants, ultimately affecting the quality of the tomato fruit and the accumulation of yield [28]. Previous studies have primarily focused on the effects of N reduction and organic fertilizer application on crops such as wheat, rice, and corn. However, in recent years, there has been an increasing amount of information about the effect of N fertilizer on tomato yield and fruit quality. Factors such as the type of N fertilizer, application period, application amount, and soil conditions in which it is applied all have a significant impact on tomato yield and fruit quality [29]. In addition, while Si has been extensively studied in relation to tomato seedlings, there has been less research on its impact on quality and yield. Therefore, in this experiment, we studied the photosynthetic characteristics of tomato plants and fruit quality (e.g., soluble sugar, sucrose, fructose, etc.) and yield under reduced N fertilization, combined with different dosages of organic and Si fertilizers. The aim was to identify the most desirable fertilization combination for promoting green, efficient, and sustainable agricultural development.

2. Materials and Methods

2.1. Site Description and Environmental Conditions

The experiment was carried out in the newly built plastic greenhouse and horticultural research room of the Horticultural Station of Shanxi Agricultural University from March 2021 to September 2021. The greenhouse has a span of 8 m and a length of 60 m. The indoor temperature was maintained at 20–30 °C during the day and 15–20 °C at night, and the indoor humidity averaged around 40%.

2.2. Soil Physiochemical Properties and Fertilizer Compositions

Before planting, soil samples were collected from the experiment site. The soil samples were then naturally air-dried and sieved through a 60-mesh sieve. The soil belongs to the cinnamon series, having a sandy loam texture, and the organic matter content of the soil was determined to be 24.7 g $C \cdot kg^{-1}$ through potassium dichromate titration. The samples were then digested by H_2SO_4–H_2O_2 digestion in a constant temperature digestion oven (BZ-JKXZ06-12B, Shanghai Biaozhuo Scientific Instrument Co., Ltd., Shanghai, China) to prepare the digestion solution [30]. The available N content in the soil was quantified as 63.0 $mg \cdot kg^{-1}$, utilizing a Kjeldahl nitrogen analyzer (SKD-200, Shanghai Peiou, Shanghai, China) with the previously described soil digestion solution [30]. The molybdenum blue colorimetric method [30] was employed to react with the digestion solution, and the effective phosphorus content was subsequently determined to be 14.4 $mg \cdot kg^{-1}$ using an ultraviolet (UV) spectrophotometer (UV-2700, Shimadzu, Tokyo, Japan) set at 650 nm. The digestion solution was further analyzed for effective potassium content using a flame atomic absorption spectrophotometer (AA-6200, Shimadzu, Japan), yielding a value of 101.9 $mg \cdot kg^{-1}$ [30].

The organic fertilizer used was mink dung soybean meal (organic matter $\geq$ 45.0%, N, P, and K $\geq$ 5.0%) which was purchased from Rongcheng Keda Fertilizer Co., LTD. Urea was used as a mineral N fertilizer (total N = 46.0%) which was purchased from Ningxia Hening Chemical Co., Ltd., Yinchuan, China. The silicon fertilizer consisted of analytical grade $Na_2SiO_3 \cdot 9H_2O$, which was purchased from Tianjin Zhiyuan chemical reagent Co., Ltd., Tianjin, China.

2.3. Plant Material, Experimental Design, and Treatments

Tomato (*S. lycopersicum* L. cultivar 'Tianxi No. 5') seeds were purchased from Shenyang Guyu Seed Industry Co., Ltd., Shenyang, China. This variety was specifically selected for its advantages in autumn and winter stubble environments. It is characterized by vigorous growth, good crack resistance, high hardness, and large fruit shape. These characteristics make it particularly suitable for growth during the test period of our study. At the five-leaf stage, when the seedlings were 4 weeks old, plants were planted in greenhouses for soil cultivation. The experiment adopted Venturi drip irrigation cultivation with water and fertilizer integration, and a total of 12 treatments were set up (the specific treatment scheme is shown in Table 1). The experiment was laid out under a randomized complete block design, three plots were set in the same greenhouse, and each treatment was repeated three times. The area of each plot was 1.2 m × 5 m, with four ridges; six tomato seedlings were planted in each ridge, and 24 plants were in each plot.

Table 1. Different treatments, showing fertilizer types and amounts/dose.

Treatments	Organic Fertilizer (M) (t/667 m^2)	Mineral Nitrogen Fertilizer (N) (kg/667 m^2)	Silicon Fertilizer (Si)
M + N	1 t	15 kg	0 mmol/L
M + N + Si	1 t	15 kg	1.5 mmol/L
M + 0.8N	1 t	12 kg	0 mmol/L
M + 0.8N + Si	1 t	12 kg	1.5 mmol/L
M + 0.6N	1 t	9 kg	0 mmol/L
M + 0.6N + Si	1 t	9 kg	1.5 mmol/L
4M + N	4 t	15 kg	0 mmol/L
4M + N + Si	4 t	15 kg	1.5 mmol/L
4M + 0.8N	4 t	12 kg	0 mmol/L
4M + 0.8N + Si	4 t	12 kg	1.5 mmol/L
4M + 0.6N	4 t	9 kg	0 mmol/L
4M + 0.6N + Si	4 t	9 kg	1.5 mmol/L

The application amounts of organic fertilizer and N fertilizer were based on by local (Taigu, Shanxi) production practices. Prior to the experiment, organic manure was applied to the soil. After the first fruit set, the applications of different amounts of N and Si fertilizers were initiated for different treatments and applied once every fortnight for a total of five applications. N fertilizers were applied into the planting soil and mixed thoroughly, averaging 0.135 kg N in one application for the normal dose and accordingly for different treatments, as follows: 0.135 kg N (M + N, M + N + Si, 4M + N, 4M + N + Si), 0.108 kg N (M + 0.8N, M + N + 0.8Si, 4M + 0.8N, 4M + 0.8N + Si), and 0.081 kg N (M + 0.6N, M + 0.6N + Si, 4M + 0.6N, 4M + 0.6N + Si). Si fertilizer was dissolved in distilled water and then applied to the soil through root irrigation, with an average of 12 L of 18 mmol of Si applied at one time per treatment. After the fifth inflorescence of tomato plants bloomed, three leaves were left upward for topping and fruit thinning, and four to five fruits were left in each cyme. Fruits were picked from the same period of time for each treatment after ripening. Briefly, all ripe fruits from each plot were harvested. From each treatment per plot, three fruits of uniform growth and ripeness were selected, and their morphological indices were determined. These fruits were then washed and processed in a juicer (209C, Haisan, Zhongshan, China) to create pulp, which formed one replicate. This process was repeated for three plots, thus forming three replicates. Afterward, the pulp was stored at −80 °C, until the determination of different quality indices.

2.4. Determination of Photosynthetic Pigments and Gas Exchange Parameters

On the 16th day of treatment, the third functional leaf of three tomato plants from each treatment in each plot was selected for sampling. Briefly, a quantity of 0.2 g of tomato leaves was introduced into a test tube filled with 20 mL of 96% ethanol and then kept in a dark environment for a duration of 24 h. Following this, the absorbance levels of the extracted pigments were determined using a spectrophotometer (UV-2450, Shimadzu, Tokyo, Japan) at wavelengths of 470 nm, 649 nm, and 665 nm. The concentrations of chlorophyll a, chlorophyll b, and carotenoids were then computed, based on a method described previously [31]. Each treatment was repeated three times. On the 18th day of treatment, the third leaf on the plant was used for measuring gas exchange parameters from 8:30 a.m. to 11:30 a.m. A Li-COR 6800 portable photosynthetic system (Li-Cor, Inc., Lincoln, NE, USA) was used to measure the photosynthetic parameters such as net photosynthetic rate (Pn), intercellular CO_2 concentration (Ci), stomatal conductance (Gs), and transpiration rate (Tr). Each treatment was repeated five times. According to the environment in the shed, the environmental parameters of the photosynthetic apparatus were set, with a flow rate of 500 µmol s^{-1} and a light intensity of 800 µmol m^{-2} s^{-1}.

2.5. Determination of Fruit Morphological Indices

The selected fruits mentioned above were used for the determination of the sample. Fruit morphological indices, such as longitudinal diameter, transverse diameter, and single fruit mass, were measured using Vernier calipers (CD-15AX, Mitutoyo Corporation, Tokyo, Japan) and electronic scales (JY1002, Shanghai Jiesheng Scientific Instrument Co., Ltd., Shanghai, China), with accuracies of 0.01 mm and 0.01 g, respectively, and each treatment was repeated three times. The fruit shape index consisted of longitudinal diameter/transverse diameter. Fruit hardness was measured by a GY-4 series digital explicit fruit hardness tester (Boshi Electronic Instrument, Hangzhou, China), and each treatment was repeated three times. At the maturity stage, the yield of listed tomato plants was measured and recorded with an electronic scale, with a precision of 0.01 g at each picking. At the fruit ripening stage, the yield of tomato plants in each treatment was measured and recorded using an electronic scale with an accuracy of 0.01 g per pick. The total yield of 24 tomato plants in the same block group in each plot was calculated cumulatively, and the final yield was converted by the planting density of the experiment, with three replications per treatment [32].

2.6. Determination of Biochemical Indices Relating to Fruit Quality

Fruit pulp samples, prepared using the aforementioned experimental methods, were utilized to determine fruit quality indicators. Soluble solids were measured directly with a digital refractometer (RHBO-90 handheld refractometer, Link-Co., Ltd., Taiwan, China). A sample of 0.1 g was weighed, placed in 50 mL of water, and boiled for 1 h to prepare the reaction solution. The soluble sugar content was determined by referring to Blunden et al. [33]. A 3 g sample was weighed, mixed well in 50 mL of water to prepare the reaction solution, and the organic acid content was determined using acid–base titration [34]. The sugar–acid ratio was calculated as soluble sugar/titratable acid. A 3 g sample was weighed and 5 mL of oxalic acid extraction reaction solution was used. Vitamin C (Vc) content was determined by molybdenum blue colorimetry [35], and lycopene was determined by referring to the method of Sharma et al. [36]. Initially, a 1.0 g sample was weighed, washed, and filtered with 20 mL of ethanol and 30 mL of methanol, then reacted with 98.0% petroleum ether and 2.00% $CHCl_2$ with the filter residue, and the filtrate was brought to 30 mL. The absorbance was measured at 502 nm. Total phenols and flavonoids were determined according to previously described methods [37]. The quantification of phenolic compounds was performed by referencing a standard curve derived from gallic acid. Firstly, a 0.5 g sample was weighed and 3 mL of 95.0% ethanol was added. It was shaken at 60 °C and extracted for 2 h. It was then centrifuged at 25.0 °C × 12,000 rpm for 10 min; the supernatant was taken and diluted to 3 mL with 95.0% ethanol. It was reacted with Folin–Ciocalteu's reagent and the absorbance was measured at 760 nm. The determination of flavonoid concentrations was based on a standard curve established using rutin. A 1 g sample was weighed, extracted with 20 mL methanol solution containing 1.00% HCl in the dark to prepare the reaction solution, and then reacted with $Al(NO_3)_3$ and NaOH. The absorbance was measured at 510 nm. Each tested parameter was repeated three times with the same number of biological repeats.

Sucrose and fructose contents were determined according to Borji et al. [38]. Sucrose synthase (SS), sucrose phosphate synthase (SPS), neutral invertase (NI), and acid invertase

(AI) activity were all determined with kits (purchased from Beijing Solarbio Technology Co., Ltd., Beijing, China). Each tested parameter was repeated three times with the same number of biological repeats.

2.7. Determination of Major Essential Elements

Root, stem, and leaf samples of tomato were taken 16 days after the first treatment with N and Si fertilizers, and tomato fruit samples were taken when the fruits were ripe. Various parts of tomato plants, including the roots, stems, leaves, and fruits, were digested using H_2SO_4–H_2O_2 [34]. A dry sample weighing 0.2 g was placed in a digestion tube, to which 3 mL of H_2SO_4 was added. The tube was then placed on the digester and subjected to a two-stage digestion process: first at 180 °C for 30 min, followed by 380 °C for 2 h. The digestion tube was allowed to stand at room temperature for a while before H_2O_2 was added. This process was repeated until the liquid became clear and transparent. The volume was then made up to 10 mL using ultra-pure water. The concentration of N was determined using the indophenol blue colorimetric method [39], while the concentration of phosphorus (P) was determined using the molybdenum-antimony resistance colorimetric method [40]. The concentrations of K, Mg, Fe, calcium (Ca), manganese (Mn), zinc (Zn), and copper (Cu) were determined using a flame atomic absorption spectrophotometer (AA-6200, SHIMADZU, Tokyo, Japan). Each parameter was tested three times, with the same number of biological replicates.

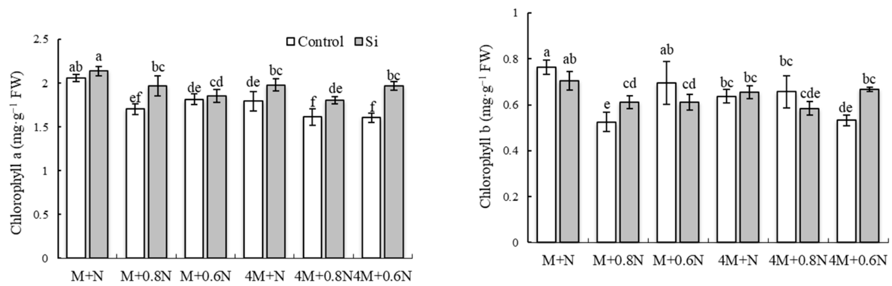
2.8. Statistical Analysis

The experimental data were analyzed by Duncan's one-way ANOVA ($p \leq 0.05$), correlation analysis, principal component analysis, and three-way ANOVA, using the Statistical Package for the Social Sciences (SPSS) version 20.0 (IBM Corporation, Armonk, NY, USA), and the data were graphed using Microsoft Excel 2010 (Microsoft Corporation, Redmond, WA, USA).

3. Results

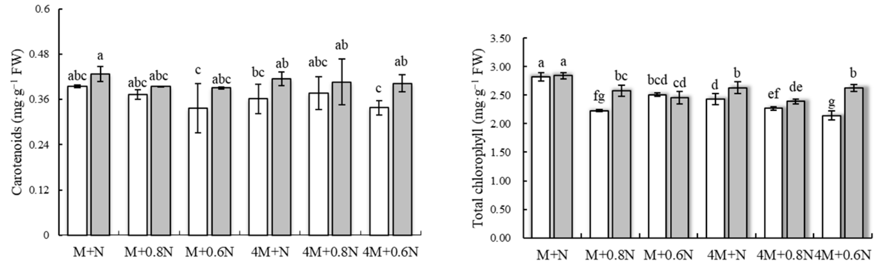
3.1. Effects of Different Doses of Chemical Nitrogen Fertilizer and Increased Organic Fertilizer Combined with Silicon Fertilizer on Photosynthetic Pigments in Tomato Plant Leaves

As shown in Figure 1, the concentrations of chlorophyll a, chlorophyll b, carotenoid, and total chlorophyll in tomato plant leaves were reduced by both treatments, i.e., reduced N fertilizer and increased organic fertilizer, when compared with M + N treatment. Seemingly, when compared with M + N treatment, the concentration of chlorophyll a, chlorophyll b, and total chlorophyll in leaves of tomato plants were significantly reduced by 21.6%, 14.0%, and 19.5% in 4M + 0.8N treatment, respectively. The concentrations of chlorophyll a, chlorophyll b, and total chlorophyll in tomato plant leaves further decreased by 22.1%, 30.3%, and 24.3% under 4M + 0.6N treatment, when compared with M + N treatment. However, the application of Si appreciably increased the concentration of photosynthetic pigment in all the respective treatments, when administered with N fertilizer.



(**A**) (**B**)

Figure 1. *Cont.*



(**C**) (**D**)

Figure 1. Effects of reducing nitrogen fertilizer and increasing organic fertilizer combined with silicon fertilizer on photosynthetic pigment concentration in tomato plant leaves. (**A**) Chlorophyll a, (**B**) chlorophyll b, (**C**) carotenoids, and (**D**) total chlorophyll concentrations. Data are shown as means ± standard deviation of three replicates. Means denoted by different letters indicate significant differences at $p \leq 0.05$.

3.2. Effects of Reducing Nitrogen Fertilizer and Increasing Silicon Fertilizer Combined with Organic Fertilizer on Photosynthetic Parameters in Tomato Plant Leaves

As shown in Figure 2A, the Pn in tomato leaves under 4M + 0.6N and 4M + 0.8N treatments significantly increased by 46.8% and 32.4%, compared with the M + N treatment. This increase in Pn was further improved with the application of Si. As shown in Figure 2B, the increased application of organic fertilizer reduced the Ci of tomato plant leaves, and the Ci of each treatment showed an inconsistent trend after Si application. Figure 2C showed that reducing N fertilizer and increasing organic fertilizer application had no significant effect on Gs of tomato plant leaves, but Gs increased after Si application. As can be seen from Figure 2D, the Tr of tomato leaves under 4M + 0.6N treatment was significantly higher than that under M + N treatment. Si application in all treatments except M + 0.8N basically reduced the Tr of leaves.

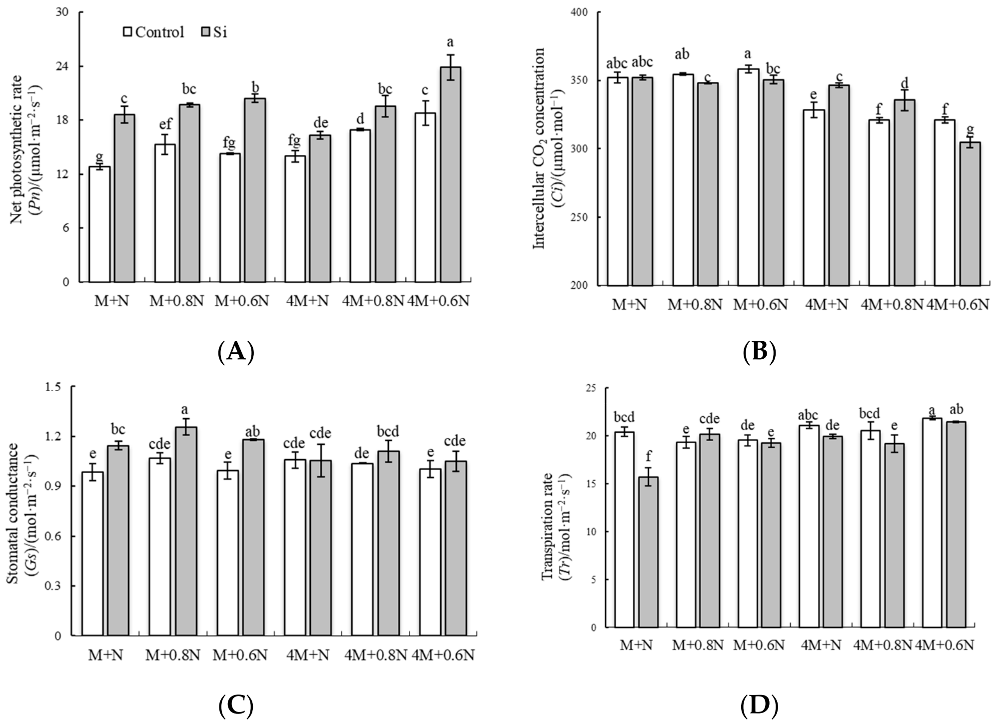


Figure 2. Effects of reducing nitrogen fertilizer and increasing organic fertilizer combined with silicon fertilizer on photosynthetic parameters in greenhouse tomato plant leaves. (**A**) Net photosynthetic

rate (Pn), (**B**) intercellular CO_2 concentration (Ci), (**C**) stomatal conductance (Gs), and (**D**) transpiration rate (Tr). Data are shown as means ± standard deviation of five replicates. Means denoted by different letters indicate significant differences at $p \leq 0.05$.

3.3. Effects of Reducing Nitrogen Fertilizer and Increasing Silicon Fertilizer Combined with Organic Fertilizer on Morphology and Yield of Tomato Plants

As shown in Figure 3A, both decreasing the amount of N fertilizer and increasing the amount of organic fertilizer promoted the growth and development of tomato fruits. From the analysis of Figure 3B–G, it can be seen that reducing the amount of N fertilizer and increasing the amount of organic fertilizer could increase the longitudinal diameter, transverse diameter, hardness, single fruit quality, and yield of tomato fruits, and could reduce the fruit shape index of the fruits to different degrees. Among them, compared with M + N treatment, the longitudinal diameter, transverse diameter, hardness, single fruit mass, and yield of tomato fruit under 4M + 0.8N treatment were significantly increased by 9.8%, 12.6%, 13.8%, 9.6%, and 7.9%, respectively. A similar increasing trend in the longitudinal diameter, transverse diameter, hardness, single fruit mass, and yield of tomato fruits was noticed under 4M + 0.6N (i.e., by 12.4%, 14.6%, 4.7%, 14.5%, and 12.9%, respectively), when compared with M + N treatment plants. The application of Si further promoted the increase in longitudinal diameter, transverse diameter, hardness, and fruit yield in all treatments.

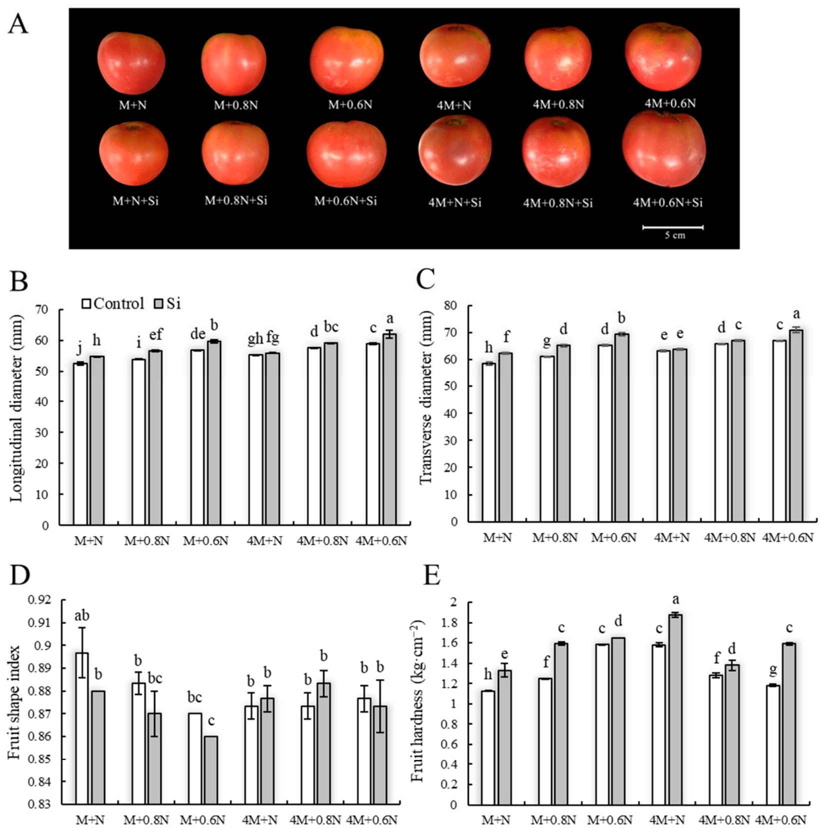


Figure 3. *Cont.*

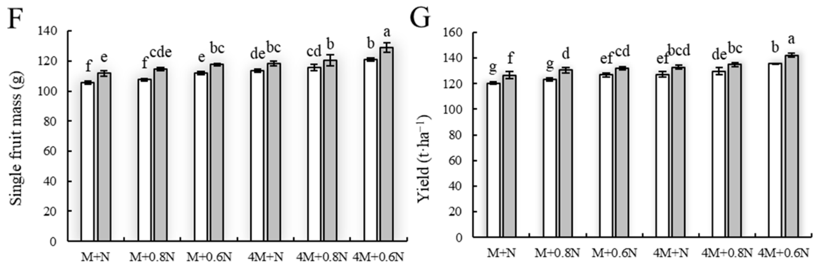


Figure 3. Effects of reducing nitrogen fertilizer and increasing organic fertilizer combined with silicon fertilizer on fruit morphology and yield of tomato plants. (**A**) Fruit phenotype, (**B**) longitudinal diameter, (**C**) transverse diameter, (**D**) fruit shape index, (**E**) fruit hardness, (**F**) single fruit mass, (**G**) yield. Data are shown as means ± standard deviation of three replicates. Means denoted by different letters indicate statistically significant differences at $p \leq 0.05$.

3.4. Effects of Reducing Nitrogen Fertilizer and Increasing Silicon Fertilizer Combined with Organic Fertilizer on the Nutritional Quality of Tomato Fruit

As shown in Figure 4A, except for 4M + 0.8N treatment, reducing N fertilizer and increasing organic fertilizer application both increased the total soluble solid of tomato fruit when compared with M + N treatment. The total soluble solid of tomato fruit was the highest under the 40.0% (0.6N) N application rate without Si application. Under Si application, the total soluble solid of tomato fruit was high under 4M + 0.8N + Si treatment than all other treatments. As shown in Figure 4B, both reducing N application and increasing organic fertilizer application reduced soluble sugar concentration in tomato fruits, which could be alleviated after Si application. Compared with M + N treatment, the soluble sugar concentration in fruits of 4M + 0.8N + Si and 4M + 0.6N + Si treatments significantly increased by 15.8% and 20.6%, respectively. As shown in Figure 4D, the titratable acid concentration in tomato fruits increased after increasing organic fertilizer application; however, the titratable acid concentration in tomato fruits decreased after reducing N application, and further reduced with Si application. The sugar–acid ratio of tomato fruits was the highest when N fertilizer was reduced by 40.0% (0.6N) without Si application, and the sugar–acid ratio of tomato fruits under 4M + 0.8N + Si treatment was the highest (Figure 4C). Under the normal application of organic fertilizer (M), reducing N fertilizer reduced the Vc concentration in tomato fruits; meanwhile, under the increased application of organic fertilizer (4M), reducing N application amplified Vc concentration in tomato fruits, and this concentration further increased with Si-application (Figure 4E). Reducing N fertilizer and increasing organic fertilizer application both increased lycopene concentration in tomato fruits (Figure 4F). The lycopene concentration under 4M + 0.8N and 4M + 0.6N treatments were significantly increased by 18.5% and 29.0%, when compared with M + N treatment, respectively. The lycopene concentration of tomato fruit was further increased after Si application. The concentrations of total phenols and flavonoids in tomato fruits increased with reducing N fertilizer application, while increasing organic fertilizer application reduced the concentrations of total phenols and flavonoids in tomato fruit. It is further noteworthy to mention that Si application promoted the concentrations of total phenols and flavonoids in tomato fruits when applied with different treatments (Figure 4G,H).

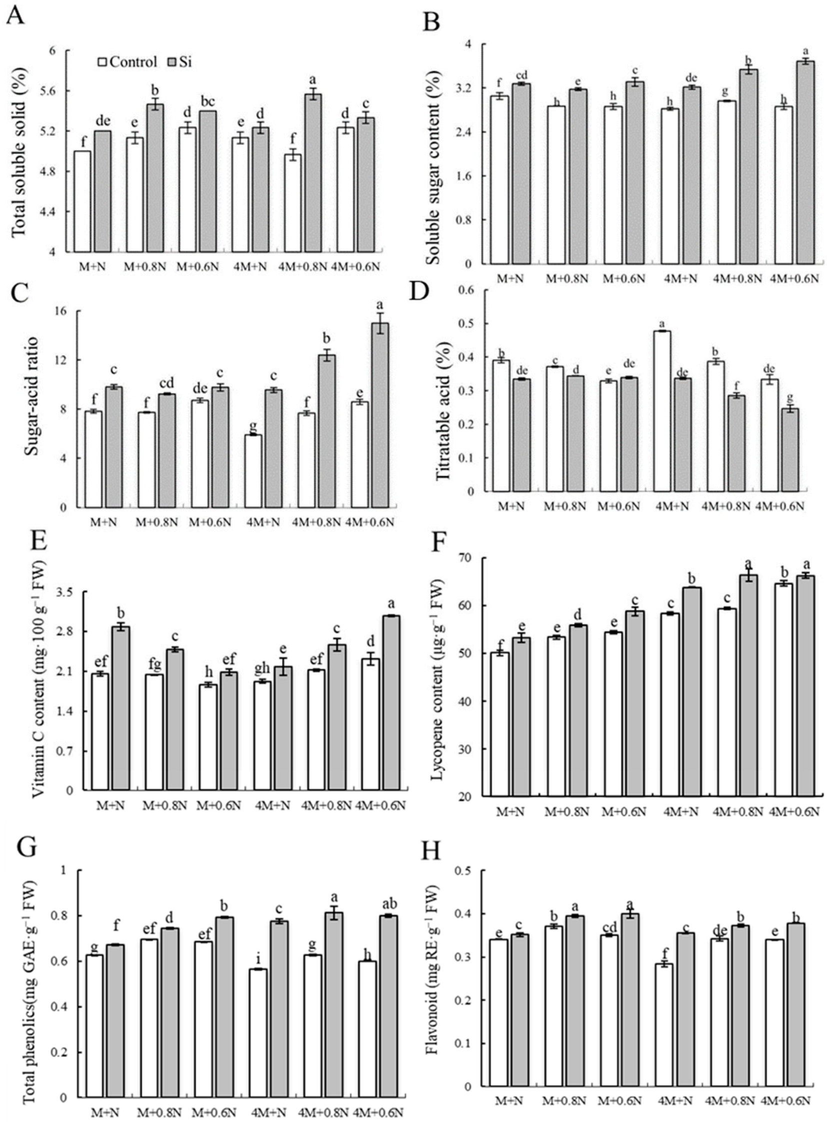


Figure 4. Effects of reducing nitrogen fertilizer and increasing silicon fertilizer combined with organic fertilizer on tomato nutritional quality. Concentrations of (**A**) total soluble solid, (**B**) soluble sugar content, (**C**) sugar–acid ratio, (**D**) titratable acid, (**E**) vitamin C, (**F**) lycopene concentration, (**G**) total phenolics, and (**H**) flavonoids in tomato fruits. mg GAE/g FW, milligrams of gallic acid equivalents per gram of fresh weight; mg RE/g FW, milligrams of rutin equivalents per gram of fresh weight. Data are shown as means ± standard deviation of three replicates. Means denoted by different letters indicate statistically significant differences at $p \leq 0.05$.

3.5. Effects of Reducing Nitrogen Fertilization and Increasing Silicon Fertilizer Combined with Increased Organic Fertilizer and Silicon Application on Sugar Metabolism in Tomato Fruit

As shown in Figure 5A–D, under a normal dose of organic fertilizer (M), the contents of sucrose and fructose and the activities of NI and AI in tomato fruits were reduced with decreased N fertilizer application, whereas the contents of sucrose and fructose and the activities of NI and AI in tomato fruits were augmented by the increased organic fertilizer (4M) dose and reduced N fertilizer application in combination. Among them, the sucrose content and NI activity in tomato fruits under the 4M + 0.6N treatment were significantly enhanced by 28.1% and 15.4%, respectively, compared with that under the M + N treatment. Si application further increased the contents of sucrose and fructose in tomato fruits, but chiefly reduced the activities of NI and AI. As shown in Figure 5E,F, under the normal amount of organic fertilizer (M) supply, a reduction in N fertilizer application increased the activities of SPS and SS in tomato fruits. The activities of SPS and SS in tomato fruits were decreased by increasing organic fertilizer application (4M). Nevertheless, the activity of SPS and SS was further increased by the Si application.

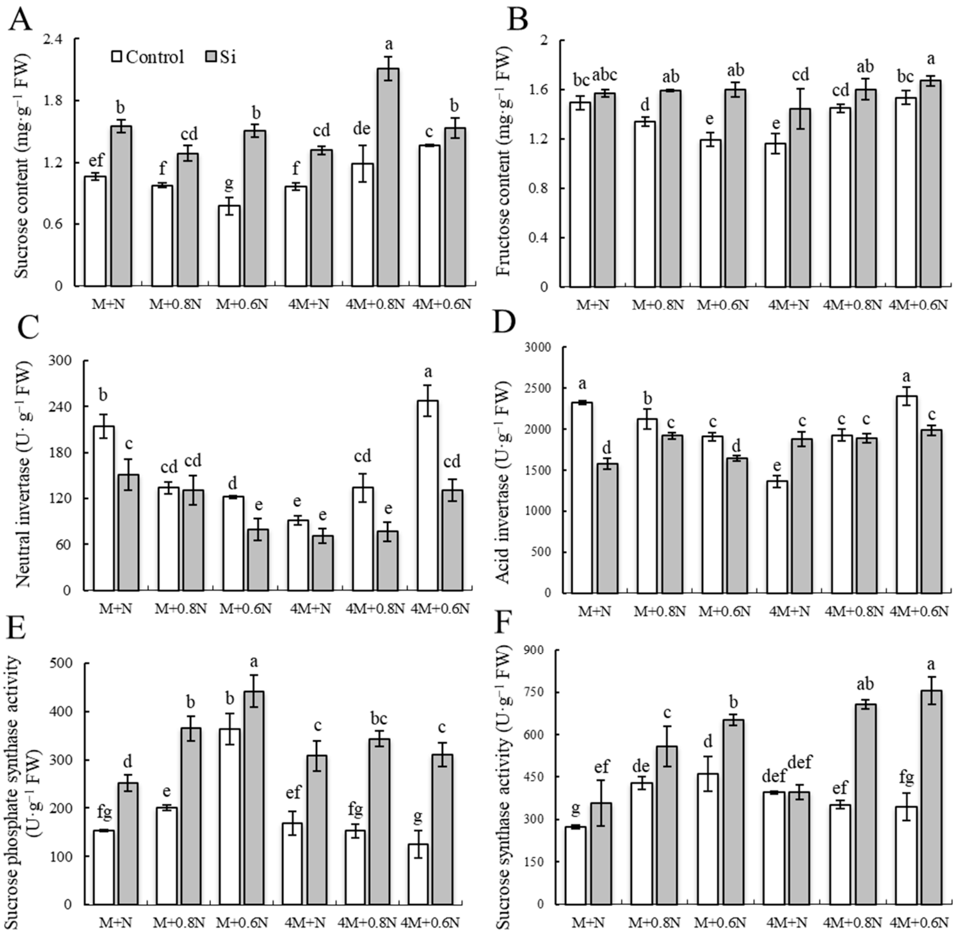


Figure 5. Effects of reducing nitrogen fertilizer and increasing silicon fertilizer combined with organic fertilizer on sugar metabolism of tomato fruit. Concentrations of (**A**) sucrose, (**B**) fructose, (**C**) NI, (**D**) AI, (**E**) SPS, and (**F**) SS in tomato fruits. Data are shown as means ± standard deviation of three replicates. Means denoted by different letters indicate statistically significant differences at $p \leq 0.05$.

3.6. Principal Component Analysis of Reducing Nitrogen Fertilizer and Increasing Silicon Fertilizer Combined with Organic Fertilizer on Yield and Quality of Tomato Fruit

The SPSS 20.0 analysis software was utilized to conduct a principal component analysis on the indicators of fruit quality and yield. The process of data analysis was simplified by reducing the dimensionality of multiple data points. An orthogonal transformation was then performed to transform correlated variables into a set of linearly uncorrelated variables, termed "principal components". Consequently, the correlation coefficients (loading matrices) between the two principal components and the eight indicators in the principal component analysis of tomato fruit yield and quality were analyzed. The results of this analysis are presented in Table 2. According to the method of Zhou et al. [41], principal component function expressions are constructed according to the calculation formula of principal components with feature vectors as weights, which can be obtained as follows:

$$Y_1 = 0.354\ X_1 + 0.309\ X_2 + 0.388\ X_3 + 0.391\ X_4 + 0.351\ X_5 + 0.304\ X_6 + 0.373\ X_7 + 0.348\ X_8 \quad (1)$$

$$Y_2 = 0.473\ X_1 + 0.130\ X_2 - 0.241\ X_3 - 0.076\ X_4 - 0.340\ X_5 + 0.653\ X_6 - 0.085\ X_7 - 0.381\ X_8 \quad (2)$$

Table 2. Principal component analysis of tomato fruit yield and quality of each factor load matrix. X_1: yield, X_2: total soluble solid, X_3: soluble sugar, X_4: sugar–acid ratio, X_5: vitamin C, X_6: lycopene, X_7: sucrose, and X_8: fructose.

Principal Component	I	II
X_1	0.834	0.475
X_2	0.729	0.131
X_3	0.915	−0.242
X_4	0.922	−0.076
X_5	0.827	−0.342
X_6	0.717	0.657
X_7	0.881	−0.085
X_8	0.820	−0.383
Eigenvalue	5.560	1.010
Contribution (%)	69.497	12.621
Cumulative contribution (%)	69.497	82.119

As shown in Table 3, through the comprehensive factor score and ranking of each treatment, the comprehensive ranking of Si treatment was better than that of no Si treatment, and the 4M + 0.6N + Si treatment ranked first. Therefore, 4M + 0.6N + Si treatment has the best comprehensive effect on tomato plant yield and quality.

Table 3. Comprehensive factor score (Y value) and ranking of each treatment.

Treatment	Y_1	Y_2	Y	Order
M + N	−2.269	−1.639	−1.784	12
M + 0.8N	−2.405	−0.388	−1.721	10
M + 0.6N	−2.479	0.638	−1.642	9
4M + N	−2.748	1.154	−1.764	11
4M + 0.8N	−1.307	0.286	−0.872	8
4M + 0.6N	0.359	1.217	0.403	5
M + N + Si	0.694	−1.903	0.242	7
M + 0.8N + Si	0.707	−0.624	0.413	4
M + 0.6N + Si	0.994	−0.038	0.686	3
4M + N + Si	0.411	0.912	0.401	6
4M + 0.8N + Si	3.696	0.341	2.611	2
4M + 0.6N + Si	4.347	0.046	3.027	1

3.7. Effect of Three Factors, Reducing Nitrogen Fertilizer, Incorporating Silicon Fertilizer, and Increasing Organic Fertilizer, on Yield and Quality of Tomato Fruits

According to the results of the three-factor ANOVA (Table 4) of the yield and quality data of tomato fruits after reducing N fertilizer, incorporating Si fertilizer, and increasing organic fertilizer showed that they all had highly significant effects on the yield and quality of tomato fruits, with the order of the effects being as follows: Si fertilizer > organic fertilizer > N fertilizer. Additionally, the interaction of all three had highly significant effects on the overall quality of tomato fruits. In terms of reducing N fertilizer, with the decreasing amount of N applied, compared with the N level, the 0.6N level all significantly improved the comprehensive quality and yield of tomato fruits; in terms of incorporation of Si fertilizer, the comprehensive quality of tomato fruits was significantly improved and the tomato yield was significantly increased by 4.74% after the application of Si fertilizer; in terms of organic fertilizer application, the increase in organic fertilizer significantly increased the sugar–acid ratio of tomato fruits, lycopene, sucrose, and vitamin C, by 5.26%, 16.26%, 18.52%, and 5.77%, respectively.

Table 4. Three-way ANOVA analysis of reducing N fertilizer and increasing Si fertilizer combined with organic fertilizer on yield and quality of tomato fruit. Different letters in the table indicate statistically significant differences at $p \leq 0.05$.

Treatments	Soluble Sugar	Total Soluble Solid	Sugar–Acid Ratio	Lycopene	Fructose	Sucrose	Vitamin C	Yield
0.6N	3.179a	5.300a	10.511a	61.039a	1.499a	1.294b	2.338a	8950.732a
0.8N	3.048b	5.283a	8.467b	58.766b	1.496a	1.391a	2.304ab	8639.042b
N	3.092b	5.142b	8.277b	56.422b	1.417b	1.225c	2.263b	8451.100c
M	3.092a	5.239a	8.848b	54.326b	1.465a	1.193b	2.237b	8440.850b
4M	3.121a	5.244a	9.322a	63.159a	1.477a	1.414a	2.366a	8919.733a
0Si	2.906b	5.117b	7.739b	56.730b	1.362b	1.055b	2.055b	8479.232b
Si	3.307a	5.367a	10.431a	60.755a	1.579a	1.552a	2.548a	8881.350a
Duncan								
M	0.063	0.742	0.000	0.000	0.619	0.000	0.000	0.000
N	0.000	0.000	0.000	0.000	0.011	0.000	0.054	0.000
Si	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
N × M × Si	0.000	0.011	0.000	0.000	0.001	0.000	0.000	0.496

3.8. Effects of Reducing Nitrogen Fertilizer and Increasing Silicon Fertilizer Combined with Organic Fertilizer on Mineral Elements' Concentrations in Different Parts of Tomato Plants

As shown in Table 4, N, Ca, and Mg concentrations in tomato plant leaves decreased with N reduction combined with increasing organic fertilizer, but the concentrations of Zn, Fe, P, and K increased. The concentrations of Mg, Zn, and Fe in leaves were further increased by reducing N fertilizer combined with Si application (Table 5; Supplementary Figure S1). The concentration of N in leaves under 4M + 0.8N treatment was significantly decreased by 11.6%, compared with M + N treatment. Compared with M + N treatment, the concentration of P in leaves under 4M + 0.8N and 4M + 0.6N treatments was significantly increased by 14.1% and 15.7%, respectively. The concentrations of N and K in tomato plant stems were decreased by reducing N fertilizer combined with increasing organic fertilizer; however, the Mg, Zn, Fe, Cu, and P concentrations were increased. Reducing N fertilizer combined with increasing organic fertilizer reduced the concentration of Ca, Mg, and N in tomato plant roots, but the concentration of P was increased. Reducing N fertilizer combined with increasing organic fertilizer improved the concentrations of N, P, and Ca in fruits, and the concentration of Zn and K decreased; meanwhile, Mg and Fe first decreased and then increased (Table 5; Supplementary Figure S1).

Table 5. Effects of reducing nitrogen fertilizer and addition of silicon fertilizer combined with increasing organic fertilizer on mineral elements concentration in leaves, stems, roots, and fruits of tomato plants. Data are shown as means ± standard deviation of three replicates. Element concentrations are expressed in gram (g) per kilogram (kg) dry weight (DW). Means denoted by different letters indicate statistically significant differences at $p \leq 0.05$.

Leaves						
Treatment	**N g/kg**	**P g/kg**	**K g/kg**	**Ca g/kg**	**Fe g/kg**	**Zn g/kg**
M + N	19.32 ± 0.98 b	3.76 ± 0.10 g	1.02 ± 0.02 f	248.33 ± 24.52 a	45.90 ± 4.11 g	5.24 ± 0.02 de
M + N + Si	17.86 ± 1.21 cd	4.19 ± 0.2 fg	1.07 ± 0.11 def	246.33 ± 26.67 a	44.10 ± 0.99 g	4.95 ± 0.20 e
M + 0.8N	16.55 ± 1.01 e	5.06 ± 0.16 c	0.91 ± 0.02 g	265.17 ± 5.93 a	47.72 ± 5.06 g	4.60 ± 0.21 f
M + 0.8N + Si	19.47 ± 0.19 bcd	4.15 ± 0.14 fg	1.05 ± 0.04 ef	147.43 ± 8.19 e	76.16 ± 3.04 bcde	5.37 ± 0.15 cd
M + 0.6N	18.32 ± 0.31 de	4.29 ± 0.06 ef	1.16 ± 0.03 cd	180.97 ± 7.39 d	67.72 ± 1.44 f	5.71 ± 0.22 bc
M + 0.6N + Si	19.07 ± 0.37 bcd	4.35 ± 0.25 ef	1.31 ± 0.02 ab	195.17 ± 3.78 bcd	71.75 ± 1.61 def	5.48 ± 0.27 bcd
4M + N	20.21 ± 1.13 a	4.94 ± 0.16 cd	1.14 ± 0.06 de	209 ± 12.97 bc	77.06 ± 1.4 bcde	5.75 ± 0.12 b
4M + N + Si	19.13 ± 0.46 bc	5.55 ± 0.22 b	1.34 ± 0.06 ab	200.1 ± 10.54 bcd	79.06 ± 0.85 abc	5.37 ± 0.09 cd

Table 5. *Cont.*

Treatment	N g/kg	P g/kg	K g/kg	Ca g/kg	Fe g/kg	Zn g/kg
Leaves						
4M + 0.8N	18.61 ± 0.35 cd	7.12 ± 0.44 a	1.07 ± 0.06 def	200.37 ± 15.22 bcd	70.78 ± 5.49 ef	6.53 ± 0.23 a
4M + 0.8N + Si	21.84 ± 0.97 bcd	4.73 ± 0.26 cde	1.08 ± 0.11 def	184.23 ± 11.10 cd	83.19 ± 1.66 a	5.84 ± 0.06 b
4M + 0.6N	19.04 ± 1.27 bcd	4.53 ± 0.15 def	1.25 ± 0.04 bc	199.23 ± 11.86 bcd	73.32 ± 0.48 cdef	6.84 ± 0.38 a
4M + 0.6N + Si	19.45 ± 0.07 bc	5.11 ± 0.49 c	1.37 ± 0.03 a	212.93 ± 12.65 b	80.1 ± 6.21 ab	5.8 ± 0.15 b
Stem						
Treatment	**N g/kg**	**P g/kg**	**K g/kg**	**Ca g/kg**	**Fe g/kg**	**Zn g/kg**
M + N	16.40 ± 0.44 a	4.24 ± 0.07 c	3.14 ± 0.01 a	175.07 ± 6.67 fg	24.10 ± 1.56 cd	20.29 ± 0.61 cd
M + N + Si	15.57 ± 0.59 ab	4.13 ± 0.24 c	2.85 ± 0.45 a	202.23 ± 10.92 bcd	23.26 ± 2.23 d	19.78 ± 1.06 cde
M + 0.8N	14.99 ± 1.00 b	4.07 ± 0.12 c	1.45 ± 0.07 b	184.20 ± 4.41 efg	25.65 ± 2.20 cd	17.85 ± 0.69 defg
M + 0.8N + Si	15.68 ± 1.15 ab	4.30 ± 0.11 c	1.67 ± 0.31 b	166.77 ± 26.27 g	23.84 ± 1.94 cd	16.66 ± 1.18 g
M + 0.6N	15.60 ± 0.55 ab	4.99 ± 0.12 a	3.00 ± 0.29 a	170.00 ± 5.46 g	27.30 ± 2.67 bcd	23.93 ± 3.4 b
M + 0.6N + Si	14.58 ± 0.22 bc	4.6 ± 0.04 b	3.06 ± 0.11 a	196.77 ± 0.8 cde	28.24 ± 6 bcd	18.37 ± 0.21 defg
4M + N	13.69 ± 0.57 cd	4.55 ± 0.15 b	3.17 ± 0.02 a	190.2 ± 6.16 def	27 ± 5.96 bcd	17.68 ± 1.25 efg
4M + N + Si	12.46 ± 0.39 ef	4.63 ± 0.26 b	3.19 ± 0.02 a	216.8 ± 1.31 ab	28.86 ± 1.63 bcd	17.13 ± 0.66 fg
4M + 0.8N	11.50 ± 0.73 f	4.75 ± 0.08 b	1.71 ± 0.04 b	212.17 ± 7.16 abc	29.53 ± 0.34 bc	21.27 ± 1.20 c
4M + 0.8N + Si	15.25 ± 0.37 ab	4.58 ± 0.13 b	2.91 ± 0.3 a	222.63 ± 7.52 a	26.51 ± 1.35 cd	20.94 ± 1.34 c
4M + 0.6N	14.77 ± 0.9 bc	5 ± 0.09 a	3.2 ± 0.03 a	203.93 ± 8.24 bcd	32.45 ± 2.23 ab	27.67 ± 0.62 a
4M + 0.6N + Si	13.16 ± 0.72 de	4.73 ± 0.06 b	3.22 ± 0.04 a	223.63 ± 5.61 a	35.64 ± 2.65 a	19.57 ± 0.6 cdef
Root						
Treatment	**N g/kg**	**P g/kg**	**K g/kg**	**Ca g/kg**	**Fe g/kg**	**Zn g/kg**
M + N	15.22 ± 0.82 a	4.56 ± 0.13 f	1.22 ± 0.21 bc	185.03 ± 6.56 ab	438.63 ± 4.62 ef	40.63 ± 1.13 b
M + N + Si	13.44 ± 0.42 bc	4.89 ± 0.10 e	1.19 ± 0.10 c	171.93 ± 6.87 bc	490.27 ± 18.32 d	33.38 ± 0.73 e
M + 0.8N	11.81 ± 1.18 cd	4.95 ± 0.10 de	1.25 ± 0.07 bc	171.43 ± 10.01 bc	460.10 ± 31.44 de	38.33 ± 1.09 c
M + 0.8N + Si	11.93 ± 1.17 cd	4.60 ± 0.10 f	1.26 ± 0.08 bc	193.67 ± 7.02 a	440.92 ± 32.52 ef	36.67 ± 1.04 d
M + 0.6N	13.86 ± 0.91 ab	5.21 ± 0.23 bc	1.27 ± 0.03 bc	172.17 ± 13.32 bc	418.05 ± 10.27 f	42.91 ± 1.09 a
M + 0.6N + Si	12.18 ± 0.17 cd	4.95 ± 0.15 de	1.2 ± 0.14 bc	181.47 ± 19.68 abc	608.37 ± 37.44 b	39.98 ± 0.66 b
4M + N	13.93 ± 0.76 ab	4.93 ± 0.17 de	1.33 ± 0.03 abc	138.67 ± 5.44 e	420.02 ± 10.45 f	31.19 ± 0.38 f
4M + N + Si	12.06 ± 0.57 cd	5.02 ± 0.05 cde	1.49 ± 0.1 a	149.53 ± 12.63 de	531.2 ± 12.15 c	26.6 ± 1.1 h
4M + 0.8N	10.92 ± 1.65 d	5.3 ± 0.14 b	1.41 ± 0.14 ab	139.77 ± 11.4 e	632.41 ± 23.63 b	28.29 ± 0.36 g
4M + 0.8N + Si	8.04 ± 0.89 e	5.04 ± 0.11 cde	1.33 ± 0.05 abc	167.1 ± 19.05 bcd	529.2 ± 9.37 c	32.01 ± 0.5 ef
4M + 0.6N	5.8 ± 0.54 f	5.53 ± 0.14 a	1.29 ± 0.06 abc	162.9 ± 9.04 cd	477.33 ± 28.87 de	40.49 ± 0.76 b
4M + 0.6N + Si	11.03 ± 0.89 d	5.18 ± 0.14 bcd	1.3 ± 0.12 abc	130.33 ± 5.25 e	669.93 ± 9.49 a	35.36 ± 1.44 d
Fruit						
Treatment	**N g/kg**	**P g/kg**	**K g/kg**	**Ca g/kg**	**Fe g/kg**	**Zn g/kg**
M + N	8.08 ± 0.13 e	4.30 ± 0.03 ef	3.20 ± 0.01 cde	71.40 ± 3.21 e	28.65 ± 2.01 de	7.68 ± 0.15 a
M + N + Si	8.48 ± 1.07 bc	4.43 ± 0.12 de	3.21 ± 0.01 bcde	80.80 ± 3.48 d	26.79 ± 1.27 de	7.05 ± 0.03 cd
M + 0.8N	9.44 ± 0.49 de	4.16 ± 0.06 f	3.23 ± 0.01 bc	85.13 ± 1.56 cd	22.40 ± 1.57 e	6.62 ± 0.14 e
M + 0.8N + Si	5.19 ± 0.42 f	4.25 ± 0.13 ef	3.19 ± 0.01 e	89.17 ± 2.31 bc	21.77 ± 1.47 e	7.02 ± 0.13 d
M + 0.6N	8.89 ± 0.34 e	4.71 ± 0.04 bc	3.19 ± 0.02 de	83.17 ± 4.01 cd	21.04 ± 0.85 e	7.12 ± 0.06 cd
M + 0.6N + Si	10.2 ± 0.24 bc	4.78 ± 0.08 b	3.19 ± 0.01 de	87.3 ± 2.17 bc	34.55 ± 2.21 d	7.26 ± 0.2 bc
4M + N	9.69 ± 0.61 bc	4.51 ± 0.12 cd	3.22 ± 0.01 bcd	93.13 ± 2.4 b	49.67 ± 4.08 bc	5.95 ± 0.14 f
4M + N + Si	10.62 ± 0.03 ab	4.86 ± 0.23 b	3.25 ± 0.01 ab	91.93 ± 0.95 b	62.38 ± 8.94 a	7.09 ± 0.07 cd
4M + 0.8N	10.93 ± 0.46 a	4.88 ± 0.21 b	3.25 ± 0.01 ab	106.37 ± 7.77 a	64.8 ± 9.12 a	7.08 ± 0.09 cd
4M + 0.8N + Si	10.14 ± 0.26 cd	4.79 ± 0.1 b	3.22 ± 0.02 bcd	101.93 ± 4.13 a	47.67 ± 4.82 bc	7.2 ± 0.12 bcd
4M + 0.6N	10.15 ± 0.66 cd	4.79 ± 0.03 b	3.27 ± 0.05 a	92.73 ± 1.5 b	44.23 ± 3.98 c	7.24 ± 0.07 bc
4M + 0.6N + Si	11.61 ± 0.33 b	5.27 ± 0.05 a	3.24 ± 0.02 ab	92.87 ± 3.18 b	53.06 ± 1.13 b	7.38 ± 0.05 b

Figure 6 shows the principal component analysis of the effect of decreasing N fertilizer and increasing silica fertilizer and organic fertilizer on mineral element concentrations in tomato leaves, stems, roots, and fruits. As shown in Supplementary Tables S1 and S2, the comprehensive factor scores and rankings of the treatments showed that the Si treatment was better than the Si-free treatment in the comprehensive analyses of both massive elements and trace elements. The M + 0.6N + Si treatment was ranked second in the comprehensive rankings. In addition, the M + 0.8N + Si treatment ranked first in the comprehensive analysis of massive elements, and the M + 0.6N + Si treatment ranked first in the comprehensive analysis of trace elements.

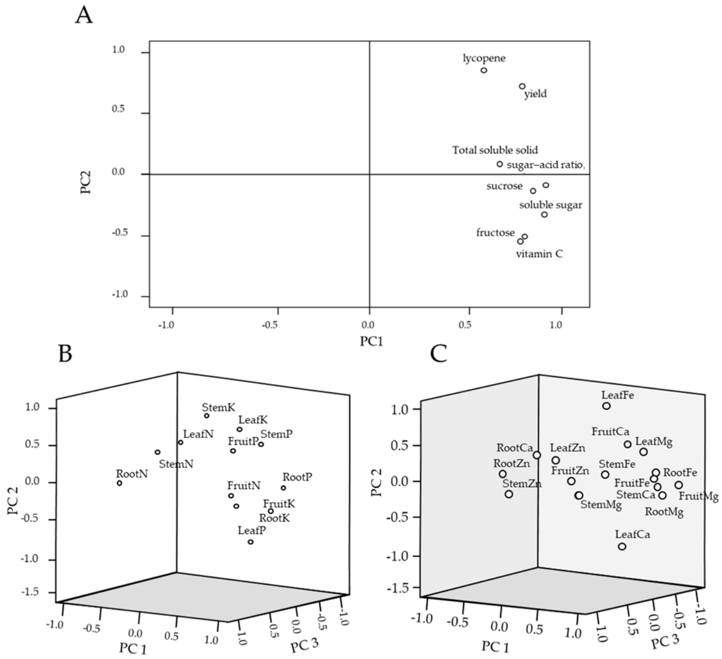


Figure 6. Principal component clustering of tomato quality, yield, and mineral element concentrations. (**A**) Principal component clustering of tomato quality and yield. (**B**) Principal component clustering of macro elements. (**C**) Principal component clustering of Ca, Mg, Fe, and Zn elements.

4. Discussion

This study revealed the effects of reduced N application on photosynthetic characteristics, fruit quality, and yield of tomato plants under different organic and silica fertilizer rates. This study provides an innovative fertilizer dosing method to optimize the N application rate in tomatoes. Farmers can refer to similar organic and silica fertilizer dosing methods to optimize N fertilizer application, reduce fertilizer use cost, and increase tomato yield in protected vegetable production facilities.

4.1. Effects of Reducing Nitrogen Fertilizer and Increasing Silicon Fertilizer Combined with Organic Fertilizer on Photosynthesis in Tomato Plant Leaves

Chlorophylls play a pivotal role in plant growth by enhancing the carbon sequestration capacity of crops and providing essential energy materials for their development and yield [42]. Within chlorophyll molecules, N constitutes approximately 75.0% of the leaf content, with a significant concentration in chlorophyll itself. Consequently, N exerts a profound influence on chlorophyll synthesis [43]. In our experimental study, we explored the impact of reducing N fertilizer while simultaneously increasing organic fertilizer levels on the chlorophyll content of tomato leaves (Figure 1). The observed reduction in chlorophyll content can be attributed to the diminished availability of N, which directly hampers chlorophyll synthesis. Additionally, the gradual release of organic fertilizer may compromise N supply [44]. Notably, our results revealed that decreasing N fertilizer and augmenting organic fertilizer application led to an enhancement in the photosynthetic rate of tomato plant leaves. This improvement was further amplified when Si was applied (Figure 2A). Although the reduction in N and the increase in organic fertilizer can theoretically reduce the synthesis of photosynthetic pigments, it is plausible that the treatment simultaneously increased the surface area of the leaf blade, thereby optimizing light reception and promoting photosynthesis [45,46]. In summary, our findings suggest that a balanced approach, involving moderate reductions in chemical N fertilizer, increased organic fertilizer, and Si application, can effectively enhance both tomato yield and quality.

4.2. Effects of Reduced Nitrogen Fertilizer and Increased Organic Fertilizer Combined with Silicon Application on Morphology and Yield of Tomato Plants

The transverse diameter, longitudinal diameter, fruit hardness, and single fruit mass of tomato greatly contribute to yield. In this experiment, reducing N application and increasing organic fertilizer application increased the yield of tomato fruit, and these parameters further increased with Si application (Figure 4). This indicates that when the ratio of soil fertilizer supply is appropriate, nutrients are predominantly channeled to fruits [47]. This improved crop yield can possibly be explained by many factors. For example, it is possible that Si can promote the increase in siliceous cells in crop epidermis, and the transmission of siliceous cells to scattered light is about 10 times that of other cells, which increases the net photosynthetic rate and improves photosynthetic efficiency, laying the foundation for higher yield in crops [48,49]. On the other hand, it may be related to the improvement in the activity of trace elements in soil by Si, thus accelerating the assimilation process of soil nitrate-N into protein and thereby improving crop yield [50].

4.3. Effect of Reduced Nitrogen Dose and Increased Organic Fertilizer Combined with Silicon Application on Pigmentation of Tomato Fruits

Lycopene is a strong antioxidant substance that imparts red color to tomato fruit, and its synthesis requires the participation of hydrolase. N fertilizer has a great influence on lycopene accumulation. An appropriate ratio of N, P, and K increases the concentration of lycopene [51,52]. Polyphenols are a major group of secondary metabolites, widely found in vegetables and fruits, and have certain effects on flavor and quality of plant products. Polyphenols also have antioxidant and cancer-prevention effects [53,54]. In this experiment, the contents of lycopene, total phenols, and flavonoids in tomato fruits increased with reduced N application. Increased application of organic fertilizer further amplified the lycopene content of tomato fruits but reduced the contents of total phenols and flavonoids. The application of Si promoted the contents of lycopene, total phenols, and flavonoids in tomato fruits under different treatments. This suggests that low N can promote the accumulation of flavonoids in plants, while high N can inhibit the corresponding synthesis [55].

4.4. Effects of Reducing Nitrogen Fertilizer and Increasing Organic Fertilizer Combined with Silicon Fertilizer on the Nutritional Quality of Tomato Fruit

The contents of soluble sugar, organic acid, total soluble solids and the sugar–acid ratio in tomato fruit are important indices to reflect fruit sugar and acidity. The sugar content of fruit is mainly determined by the soluble sugar content, and different types of sugar play different roles in tomato fruit quality. The sweetness is mainly determined by fructose and sucrose, and fructose is 1.7 times sweeter than sucrose. Therefore, changing the ratio of sucrose to fructose or increasing the content of fructose is very helpful in increasing the sweetness of tomato fruits [54,56]. In this experiment, under the treatment of increasing organic fertilizer application (4M), reduced N fertilizer increased the contents of sucrose and fructose in tomato fruits (Figure 4). It is generally believed that sugars in tomato fruits are in three phases, such as synthesis, transport, and metabolic transformation, which can be divided into the following: (1) the leaves of tomato plants produce sugars through photosynthesis [57]; (2) synthesized sugars are then transferred into cells through transporters and metabolized into sucrose [54]; (3) sucrose is transported to phloem through short distance, and then transported to fruit through sieve tube for long distance, and (4) sucrose is metabolized in fruit cells to synthesize starch or decompose into glucose and fructose [56,58]. These processes are profoundly dependent on different enzymes, such as invertase and synthase. Invertase can be divided into NI and AI, and invertase can break down sucrose into two hexose forms, fructose and glucose [41]. In this experiment, the activity of AI was significantly higher than that of NI, indicating that AI played a major role in the catalytic conversion of sucrose to reducing sugar in mature tomatoes of this variety (Figure 4). Synthases mainly include SS and SPS [56,58]. In this experiment, under the treatment of increasing organic fertilizer application (4M), reducing N fertilizer reduced the activities of SPS and SS in tomato fruits (Figure 4). SS catalyzes the reaction of free fructose with glucose donor uridine diphosphate glucose (UDPG) to produce sucrose, and the level of SPS activity affects the synthesis ability of sucrose and the distribution of photocontracted carbon between starch and sucrose [54,58]. The results showed that increasing organic fertilizer and decreasing N fertilizer could decrease sucrose synthesis ability but did not decrease sucrose content in fruit.

4.5. Principal Component Analysis of Reducing Nitrogen Fertilizer and Increasing Organic Fertilizer and Silicon Treatment on Yield and Quality of Tomato Fruit

Principal component analysis (PCA) is an effective method for comprehensive evaluation. It can transform several variables with certain correlations into several unrelated comprehensive variables, and its variance contribution rate can be used as the weight to construct a quantifiable comprehensive evaluation system [41]. The accumulative contribution rate of the first two principal component quality factors was more than 82.1%, which retained most of the information of the original data. Therefore, the information on the first two principal component quality factors was extracted for subsequent analysis and calculation. According to the characteristic vectors of quality factors of each principal component, the contribution rate of the first principal component reaches 69.5%, which mainly represents the sugar–acid ratio, sucrose, soluble sugar, fructose and Vc contents, reflecting the fruit taste quality. According to the comprehensive evaluation model, comprehensive scores of tomato fruit quality of each treatment were calculated. Without Si treatment, the top three comprehensive scores were noticed in 4M + 0.6N, 4M + 0.8N, and M + 0.6N treatments, respectively. The results showed that the comprehensive quality of tomato fruit could be improved by appropriate reduction in N application on the basis of the current normal N application rate. On this basis, the root application of Si fertilizer could further improve the comprehensive quality of tomato fruit. Considering all the factors, reducing N and increasing organic fertilizer combined with Si application could significantly improve the comprehensive quality of tomato fruit (Figure 7).

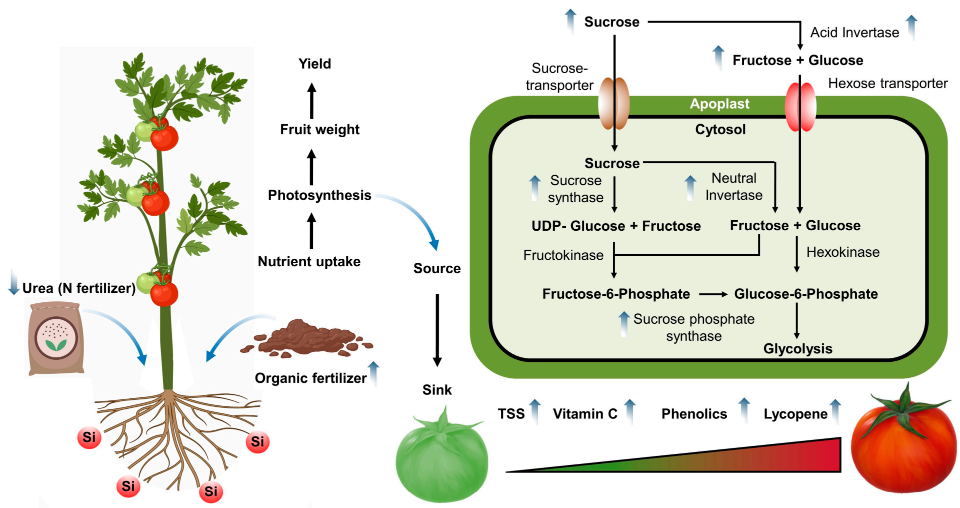


Figure 7. A working model showing how the regulation of photosynthesis and sugar metabolism, through reducing chemical nitrogen supply and increasing organic fertilizer and silicon, improves tomato yield and quality.

4.6. Effect of Three Factors: Reducing Nitrogen Fertilizer, Incorporating Silicon Fertilizer and Increasing Organic Fertilizer on Yield and Quality of Tomato Fruits

A multifactor ANOVA was used to examine the role and effect of two or more factors on the dependent variable and the effect of these factors acting together. This method is based on the principles of analysis of variance (ANOVA) and uses the process of hypothesis testing to determine whether more than one factor has a significant effect on the dependent variable. Models for multifactor ANOVA usually include the main effects of factors and interaction effects between factors. The main effect refers to the effect of one factor alone on the dependent variable, while the interaction effect refers to the effect of two or more factors together on the dependent variable. Therefore, the experiment firstly analyzed the variance of tomato fruit quality and yield data according to the three independent variables of reducing N fertilizers, incorporating Si fertilizers, and increasing organic fertilizers, comparing their total deviation squared and the proportion accounted for by each part, and then concluded that reducing N fertilizers, incorporating Si fertilizers, and increasing organic fertilizers had a highly significant effect on tomato fruit yield and quality. The size of the effect descended in the following order: Si fertilizers>organic fertilizers>N fertilizers, and the interaction also had a highly significant effect on the overall quality of tomato fruit (Table 4).

4.7. Effects of Reducing Nitrogen Fertilizer and Increasing Organic Fertilizer Combined with Silicon Treatment on Mineral Element Concentrations in Different Parts of Tomato Plants

In this study, we measured the concentration of mineral elements in the roots, stems, leaves, and fruits of tomato plants. We found that the amount of N accumulation in different tissues followed this descending order: leaf > stem > root > fruit. By reducing N application and increasing organic fertilizer application, the N concentration in the leaves, stems, and roots of tomato plants decreased. However, this led to an increase in the accumulation of N concentration in the fruits. After applying Si, the N concentration in the fruits increased even further. This could be because Si adsorption promoted the absorption and utilization of N in tomato plants, thereby improving N use efficiency [53]. Other elements exhibited diverse trends in different parts of the plant. This phenomenon could be attributed to two factors: firstly, the demand for each element varies in different periods; secondly, different elements have varying mobility and distribution positions, leading to inconsistent trends of elements in different tissues and organs [59].

5. Conclusions

Reducing the use of N fertilizer in crop production is a significant issue in agriculture. One strategy to achieve this reduction involves increasing the use of organic fertilizers, beneficial elements, and microbes. Our study investigated the impact of reducing N application on the photosynthetic characteristics, fruit quality, and yield of tomato plants, given varying rates of organic and silica fertilizers. We found that reducing N fertilizer by 40.0%, increasing organic fertilizer fourfold, and incorporating Si treatments led to an increase in the photosynthetic rate and accumulation of photosynthetic products. This combination ultimately improved both the quality and yield of the fruit. Principal component analysis and three-way ANOVA of fruit yield and quality indicators showed that reducing N fertilizer, incorporating Si fertilizer, increasing organic fertilizer, and the interaction of all three had significant effects on tomato fruit yield and quality, and the 4M + 0.6N + Si treatment had the best positive effect on tomato yield and quality. The findings offer an innovative approach to fertilizer dosing, aimed at optimizing the rate of N application in tomato cultivation. Moreover, this method can serve as a reference for farmers seeking to optimize their use of nitrogen fertilizer, thereby reducing costs and enhancing tomato yield in protected vegetable production facilities.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy14050966/s1. Supplementary Figure S1: effects of different fertilizer treatments on Mg concentration in different tissues of tomato plants. Supplementary Table S1: the comprehensive factor score (Y value) of macroelements-related indicators and the ranking of each processing method. Supplementary Table S2: the comprehensive factor score (Y value) of trace elements related indicators and the ranking of each treatment method.

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writing—review and editing. J.G.: formal analysis. L.H.: investigation, formal analysis, and writing—review and editing. Y.Z. (Yi Zhang): conceptualization, funding acquisition, project administration, resources, supervision, and writing—review and editing. G.J.A.: conceptualization, writing—review and editing, and funding acquisition. All authors have read and agreed to the published version of the manuscript.

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