horticulturae

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Effect of Foliar Application of Silicon and Selenium on the Growth, Yield and Fruit Quality of Tomato in the Field

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Abstract: Tomato (*Solanum lycopersicon*) is a widely produced and consumed fruit vegetable worldwide. Silicon (Si) and selenium (Se) can promote crop growth and development. However, the effects of these elements on tomato fruit quality have not been investigated comprehensively, nor are their combined effects on yield and quality clear. The aim of this study was to investigate the effects of foliar application of Si and Se on tomato growth, yield and fruit quality. The tomato plants were foliarly applied with 1 mM Si and 25 µM Se individually or in combination, and the experiment was carried out in a plastic arch shed at Yangling in spring. Our results demonstrated improved plant growth by application of Si and Se, with the effect of combined treatment being more obvious. Application of Si individually or in combination with Se increased the yield. Se addition increased the concentrations of soluble sugars, vitamin C, phenols, anthocyanin, lycopene, carotenoids, Se and protein, and decreased the nitrate level, but did not affect the concentration of total organic acids in the fruit. Si application induced similar changes to Se addition in the levels of sucrose and protein in the fruit, but had no effect on other quality traits. The combined Si and Se treatment did not show significant superior effects on the fruit quality over their individual applications. Our results suggest that Si and Se application improved the tomato plant growth. Si and Se application, respectively, had obvious effects in the yield increase and quality improvement, and the combined treatment had positive effects on both aspects. The study may provide a theoretical base for the application of Se and Si fertilizers in tomato production.

Keywords: tomato (*Solanum lycopersicon*); silicon; selenium; plant growth; yield; fruit quality

Citation: Hu, W.; Su, Y.; Yang, R.; Xie, Z.; Gong, H. Effect of Foliar Application of Silicon and Selenium on the Growth, Yield and Fruit Quality of Tomato in the Field. *Horticulturae* **2023**, *9*, 1126. https://doi.org/10.3390/horticulturae9101126

Academic Editor: Moreno Toselli

Received: 22 September 2023
Revised: 9 October 2023
Accepted: 10 October 2023
Published: 12 October 2023

1. Introduction

Tomato (*Solanum lycopersicon*) belongs to the order Tubiflorae and family Solanaceae, being a dicotyledonous plant. It is an economically important vegetable, and gains popularity among consumers due to its abundant nutrients [1,2]. Increasing tomato yield is important to guarantee sufficient market supply. On the other hand, with the improvement of people's living standards in recent years, the consumer market shows an increasing demand for high-quality tomatoes. Although not considered essential elements for plants, both silicon (Si) and selenium (Se) are beneficial for plant growth and development [3,4]. Moreover, Si and Se are beneficial to the human health [5–7]. Therefore, application of these elements may be a feasible pathway to improve the yield and quality of tomato.

Si is the second most abundant element in the earth's crust [8]. Despite this, most of the Si is insoluble in the soil solution and thus unavailable for plant uptake [9]. Therefore, exogenous application of Si is an effective method for Si biofortification, especially for low-Si-accumulating plants, such as tomato [10]. The positive effects of Si on the yield and quality have been reported in different plants, such as apple [11], avocado [12], rice [13], wheat [14], corn salad [15], pepper [16], cucumber [17]. The effects of Si on plant growth, yield and some quality traits have also been investigated in tomato. Xue et al. [18] reported that Si spraying increased the single fruit weight and levels of soluble sugar and vitamin C, while reducing the nitrate and titratable acid levels in the fruit. Gao and Cao [19] found that Si supplementation in a hydroponic system increased the fruit number and yield per plant, but decreased the single fruit weight. Jalali et al. [20] observed that foliar application of Si increased the fruit firmness, fruit volume, yield per plant, titratable acidity and concentrations of soluble solids and carbohydrate in the fruit. In addition, Zhao et al. [21] observed a Si-mediated increase in the phenol concentration in the fruit; however, Costan et al. [22] did not observe any effect. These studies have shown differential effects of applied Si, implying the need for more investigations. Moreover, little information is available on Si's effect on the levels of individual sugars and organic acids in tomato fruits. Therefore, a comprehensive investigation of the effect of Si on the fruit quality of tomato is needed.

Se is an essential component of selenoaminoacids, selenoproteins, glutathione peroxidase and thioredoxin reductase [23–25], and, thus, performs crucial biological functions in the cell. The positive effect of Se on yield and/or quality has been reported in peach [26], pear [26], rice [27], millet [28], cucumber [17], lettuce [29], basil [30]. The effect of Se application on yield and quality has also been investigated in tomato. Carvalho et al. [31] reported that root application of organic Se did not change the yield. Liu et al. [32] also observed that foliar spraying of sodium selenite did not affect the single fruit weight, fruit number or yield. In contrast to these results, Hernandez-Hernandez et al. [1], Neysanian et al. [33] and Jalali et al. [20] found that Se application increased tomato yield. Previous scholars have focused on different fruit quality traits and observed some differential results of Se's effects in tomato. For instance, Zhu et al. [2] observed that foliar spraying of Se increased the concentrations of soluble sugars, amino acids, glutathione, vitamin C, vitamin E and flavonoid in the fruit, whereas it did not change the levels of lycopene or organic acids. Neysanian et al. [33] reported that foliar spraying of appropriate doses of sodium selenate and Se nanoparticles increased the postharvest longevity of tomato. Liu et al. [32] found that Se spraying increased the contents of soluble solids, titratable acid and soluble sugars, but did not affect the vitamin C level in the fruit. Jalali et al. [20] found that foliar application of sodium selenite increased the fruit firmness and the contents of total soluble solids and titratable acid in the fruit, but did not change the fruit carbohydrate level. However, as of this writing, less information is available on the effects of Se on the concentrations of different soluble sugar and organic acid components and phenols, as well as nitrate in tomato fruits.

The effect of combined Si and Se treatment on the growth, yield or quality has been investigated in some crops. For instance, the superior effect of combined Si and Se treatment has been observed in orange [34] and mango [35], but not in rice [13], implying the need to investigate the combined effects in different plant species. In tomato, little information is available on the combined effects of these two elements on the growth, yield and fruit quality. The purpose of this study was to investigate the effects of foliar spraying of Si and Se separately or in combination on the plant growth, yield and nutrient quality of tomato fruits. The study may provide basic knowledge about the possibility of the application of Se and Si fertilizers in tomato production.

2. Materials and Methods

2.1. Plant Material and Treatment

The seeds of tomato 'Chulian 1' were soaked in 0.1% carbendazim solution for 30 min, and sterilized in a water bath at 55 °C for 20 min. The seeds were then soaked in distilled water for 8 h at room temperature, after which they were germinated on moist filter paper in petri dishes at 30 °C in the dark. The germinated seeds were sown in plug trays filled with a mixed substrate composed of peat, vermiculite and perlite (2:1:1, *v:v:v*) and transferred to a greenhouse at a poverty alleviation site in Yangling, Shaanxi, China, with natural sunlight. The temperature was 25–30 °C in the daytime and 15–18 °C at night. When the third leaves were fully expanded, uniform seedlings were transplanted in a plastic arch shed at the same site with a plant density of 5 plants/m^2. Before transplanting, farm manure was applied as the base fertilizer at 850 kg/667 m^2. The plants were regularly watered, and pest and disease prevention and control adhered to the plant protection policy of combining physical and chemical controls. The concentrations of available Si and Se in the soil were 22.08 mmol kg^{-1} and 3.42 µmol kg^{-1}, respectively.

For Si and Se treatment, the plants were foliarly sprayed with sodium silicate and sodium selenite at the fruit setting and expansion stage of the third truss. There were five treatments: (a) CK (control, H_2O); (b) Na (1.0 mM sodium sulfate); (c) Si (1.0 mM sodium silicate); (d) Se (25 µM sodium selenite plus 1.0 mM sodium sulfate); and (e) Si + Se (1.0 mM sodium silicate plus 25 µM sodium selenite). Each treatment had 3 ridge replications, and there was a total of 150 plants. The applied Si concentration was referred to Gao and Cao [19] and Li et al. [36], and the application rate of Se was based on our preliminary trial. To balance the concentration of sodium introduced by Si spraying, 1.0 mM sodium sulfate was supplemented in the Se-applied treatments. The 'Na' treatment was set to investigate the possible effect of sodium. The solution pH was adjusted to 6.0 with sulfuric acid or sodium hydroxide, and was evenly sprayed on tomato leaves.

Fifteen days after the second application of Si and Se, the morphological indices were assayed. When the third truss of fruits were at the commercial ripening stage, eighteen fruits with the same orientation were randomly harvested from each treatment, and quickly washed with deionized water. The fruits were smashed, homogenized into juice, and stored at −80 °C until analysis.

2.2. Plant Growth and Fruit Yield

Fifteen days after the second Si and Se application, the plant height (cm) and stem diameter (mm) were assayed, and the leaf number was counted. To analyze the yield traits, the individual commercial fruits were weighed, and the cumulative yield and fruit number per plant were recorded. The single fruit weight and yield per plant were expressed in grams and kilograms, respectively. The longitudinal and transverse diameters of fruits were measured with a vernier caliper, and the fruit shape index was calculated by dividing the longitudinal diameter by the transverse diameter.

2.3. Measurement of Si and Se Concentrations

Si and Se concentrations in tomato fruits were respectively determined using molybdenum blue colorimetry and a liquid chromatography–atomic fluorescence spectrometer (LC-AFS8530, Haiguang Instrument Co., Beijing, China) as described in our previous study [17]. The Si and Se concentrations were expressed in milligrams per kilogram of fresh sample.

2.4. Determination of Carbohydrate and Organic Acid Concentrations

The extraction and determination of soluble sugars, starch and organic acids in tomato fruits were conducted following the procedure of our previous study [17]. The concentrations of soluble sugars were measured with an ion chromatograph equipped with integral pulse amperometric detection (ICS-5000+, Thermo Fisher, Waltham, MA, USA). The starch concentration was measured with the anthrone colorimetric method. The concentrations of organic acids were measured with an ultra-high-performance liquid chromatographer (UHPLC, Shimadzu corporation, LC-30 A, Kyoto, Japan) equipped with a C18 reversed-phase column and a photodiode detector. The results were expressed in milligrams per gram of fruit.

2.5. Determination of Concentrations of Soluble Protein, Free Amino Acid and Nitrate

The soluble protein concentration in tomato fruits was determined with the Coomassie brilliant blue G-250 staining method [37]. Total free amino acid concentration was measured by ninhydrin colorimetry [38], and nitrate concentration was determined by salicylic acid colorimetry [39]. The concentrations of soluble protein and total free amino acid were expressed in milligrams per gram of fruit, and the nitrate concentration in micrograms per gram.

2.6. Determination of Secondary Metabolites in Tomato Fruits

The concentration of vitamin C in tomato fruits was measured by the colorimetric method using 2,6-dichlorophenol [17], and the concentrations of total phenols and flavonoids were respectively determined by sodium carbonate colorimetry and aluminum chloride colorimetry as described previously [1]. The anthocyanin concentration was measured by vanillin hydrochloric acid colorimetry [40]. The concentrations of lycopene and β-carotene were determined and calculated according to the method described by Petropoulos et al. [41]. The concentrations of vitamin C, total phenols and flavonoids were expressed in micrograms per gram of fruit, and the concentrations of lycopene, β-carotene and total carotenoids in milligrams per kilogram. The anthocyanin concentration was expressed in nanomoles per gram.

2.7. Statistical Analysis

The data were subjected to analysis of variance and Tukey's test using SPSS 21.0 (SPSS, Inc., Chicago, IL, USA), and TOPSIS was used for comprehensive evaluation of yield and quality [42].

3. Results

3.1. Plant Growth

In this experiment, the 'Na' treatment was set to investigate the possible effect of Na introduced by applied sodium silicate. The results demonstrated that 2 mM Na had no significant effect on the growth, yield or quality of tomato compared with the control (Tables 1–5; Figures 1 and 2), indicating that the effect of applied sodium silicate was from Si, rather than Na. In this study, we mainly compared the effect of Si and Se with that of the 'Na' treatment.

Compared with the 'Na' treatment, spraying Si or Se alone increased the stem diameter, but they did not change the plant height or leaf number (Table 1). The combined application of Si and Se increased these growth parameters significantly (Table 1).

Table 1. Effect of Si and Se application on the growth of tomato plants.

Treatment	Plant Height (cm)	Stem Diameter (mm)	Number of Leaves
CK	208.1 ± 6.7 ab	9.3 ± 0.3 b	18.7 ± 0.7 ab
Na	207.3 ± 5.6 b	9.3 ± 0.2 b	18.6 ± 0.7 b
Si	206.4 ± 5.2 b	10.0 ± 0.3 a	19.3 ± 0.7 ab
Se	211.4 ± 4.8 ab	9.8 ± 0.3 a	18.8 ± 0.6 ab
Si + Se	213.2 ± 5.7 a	9.8 ± 0.4 a	19.3 ± 1.2 a
F test	**	***	*

Data are shown as means ± SD (n = 18). Values followed by different letters indicate significant differences among treatments ($p < 0.05$). CK, control (H_2O); Na, 1.0 mM Na_2SO_4; Si, 1.0 mM Na_2SiO_3; Se, 25 µM Na_2SeO_3 + 1.0 mM Na_2SO_4; Si + Se, 1.0 mM Na_2SiO_3 + 25 µM Na_2SeO_3. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

3.2. Yield-Related Traits

Compared with the 'Na' treatment, spraying Si alone or in combination with Se significantly increased the per-plant yield, whereas applied Se alone did not affect these parameters (Table 2). Se and Si did not affect the single fruit weight or fruit shape index, regardless of whether they were applied individually or in combination (Table 2).

3.3. Si and Se Concentrations in the Fruit

The Si concentration in the fruit was not significantly changed as a result of the application of Si or Se (Figure 1A). Se application alone or in combination with Si significantly increased Se concentration in the fruit, whereas spraying Si alone did not affect the Se accumulation (Figure 1B).

Table 2. Effects of Si and Se application on the yield-related traits and fruit shape index of tomato.

Treatment	Yield per Plant (kg plant^{-1})	Fruit Number per Plant	Single Fruit Weight (g)	Fruit Shape Index
CK	1.62 ± 0.40 bc	17.3 ± 3.6 b	93.2 ± 9.3	0.77 ± 0.06
Na	1.59 ± 0.30 c	17.6 ± 3.6 ab	91.6 ± 13.5	0.77 ± 0.06
Si	1.83 ± 0.36 ab	19.7 ± 3.1 a	93.5 ± 13.4	0.77 ± 0.05
Se	1.75 ± 0.30 abc	19.1 ± 2.2 ab	91.6 ± 9.8	0.75 ± 0.06
Si + Se	1.93 ± 0.29 a	19.8 ± 3.2 a	98.1 ± 9.8	0.76 ± 0.04
F test	***	**	ns	ns

Data are shown as means ± SD (n = 18 for fruit shape index and 30 for other parameters). Values followed by different letters indicate significant differences among treatments ($p < 0.05$). CK, control (H_2O); Na, 1.0 mM Na_2SO_4; Si, 1.0 mM Na_2SiO_3; Se, 25 µM Na_2SeO_3 + 1.0 mM Na_2SO_4; Si + Se, 1.0 mM Na_2SiO_3 + 25 µM Na_2SeO_3. ** $p < 0.01$, *** $p < 0.001$; ns, not significant at $p < 0.05$.

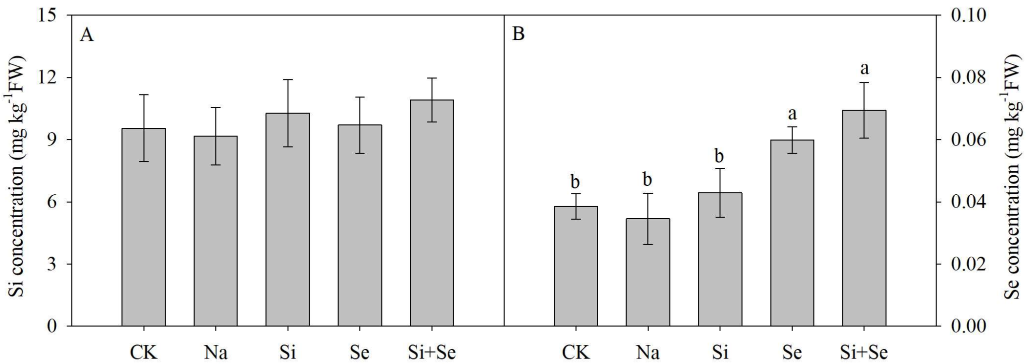

Figure 1. Effect of foliar application of Si and Se on the concentrations of Si (**A**) and Se (**B**) in tomato fruits. Data are shown as means ± SD (n = 4). Different letters above bars indicate significant differences among treatments ($p < 0.05$). CK, control (H_2O); Na, 1.0 mM Na_2SO_4; Si, 1.0 mM Na_2SiO_3; Se, 25 µM Na_2SeO_3 + 1.0 mM Na_2SO_4; Si + Se, 1.0 mM Na_2SiO_3 + 25 µM Na_2SeO_3.

3.4. Carbohydrate Concentrations in the Fruit

Compared with the 'Na' treatment, spraying Si alone increased the sucrose concentration, but did not affect the concentrations of other sugars (Table 3). Regardless of the presence of added Si, Se application increased the total carbohydrate concentration by promoting the levels of various soluble sugars (Table 3). Neither Si nor Se treatment affected the starch concentration in the fruit (Table 3).

Table 3. Effect of Si and Se application on the carbohydrate concentrations of tomato fruits.

Treatment	Glucose (mg g^{-1})	Fructose (mg g^{-1})	Sucrose (mg g^{-1})	Starch (mg g^{-1})	Total Carbohydrates (mg g^{-1})
CK	6.66 ± 0.41 ab	3.39 ± 0.29 ab	0.44 ± 0.07 c	3.01 ± 0.11	13.5 ± 0.8 c
Na	6.12 ± 0.14 b	3.17 ± 0.08 b	0.38 ± 0.03 c	2.83 ± 0.30	12.5 ± 0.4 c
Si	6.72 ± 0.54 ab	3.57 ± 0.35 ab	0.62 ± 0.03 b	3.40 ± 0.25	14.3 ± 1.0 bc
Se	7.19 ± 0.17 a	3.83 ± 0.09 a	0.78 ± 0.04 ab	3.87 ± 0.72	15.7 ± 0.5 ab
Si + Se	7.37 ± 0.19 a	3.87 ± 0.18 a	0.88 ± 0.10 a	4.20 ± 1.08	16.3 ± 0.8 a
F test	**	*	***	ns	***

Data are shown as means ± SD (n = 3). Values followed by different letters indicate significant differences among treatments ($p < 0.05$). Total carbohydrate = glucose + fructose + sucrose + starch. Hexose = glucose + fructose. CK, control (H_2O); Na, 1.0 mM Na_2SO_4; Si, 1.0 mM Na_2SiO_3; Se, 25 µM Na_2SeO_3 + 1.0 mM Na_2SO_4; Si + Se, 1.0 mM Na_2SiO_3 + 25 µM Na_2SeO_3. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$; ns, not significant at $p < 0.05$.

3.5. Organic Acid Concentrations in the Fruit

In the tomato fruit, citric acid was the most abundant organic acid, followed by tartaric acid, malic acid and acetic acid (Table 4). Compared with the 'Na' treatment, neither single nor combined application of Si and Se changed the concentrations of individual or total organic acids in tomato fruits (Table 4).

Table 4. Effect of Si and Se application on the organic acid concentrations of tomato fruits.

Treatment	Citric Acid ($mg\ g^{-1}$)	Malic Acid ($mg\ g^{-1}$)	Tartaric Acid ($mg\ g^{-1}$)	Acetic Acid ($mg\ g^{-1}$)	Total Organic Acids ($mg\ g^{-1}$)
CK	4.07 ± 0.33 b	0.88 ± 0.11	0.96 ± 0.08	0.59 ± 0.05	6.50 ± 0.52
Na	4.35 ± 0.27 ab	0.75 ± 0.04	0.89 ± 0.04	0.57 ± 0.03	6.56 ± 0.31
Si	4.70 ± 0.08 a	0.83 ± 0.12	0.99 ± 0.09	0.53 ± 0.18	7.05 ± 0.37
Se	4.62 ± 0.15 ab	0.76 ± 0.08	1.02 ± 0.05	0.32 ± 0.10	6.72 ± 0.27
Si + Se	4.80 ± 0.19 a	0.78 ± 0.11	1.07 ± 0.09	0.34 ± 0.09	6.99 ± 0.48
F test	*	ns	ns	*	ns

Data are shown as means ± SD (n = 3). Values followed by different letters indicate significant differences among treatments ($p < 0.05$). CK, control (H_2O); Na, 1.0 mM Na_2SO_4; Si, 1.0 mM Na_2SiO_3; Se, 25 µM Na_2SeO_3 + 1.0 mM Na_2SO_4; Si + Se, 1.0 mM Na_2SiO_3 + 25 µM Na_2SeO_3. * $p < 0.05$; ns, not significant at $p < 0.05$.

3.6. Concentrations of Soluble Protein, Free Amino Acid and Nitrate in the Fruit

Compared with the control, or 'Na' treatment, both individual and combined application of Si and Se increased the soluble protein concentration (Figure 2A), while decreasing the nitrate level in the fruit (Figure 2C). The concentration of free amino acid was not significantly changed by Si or Se treatment (Figure 2B).

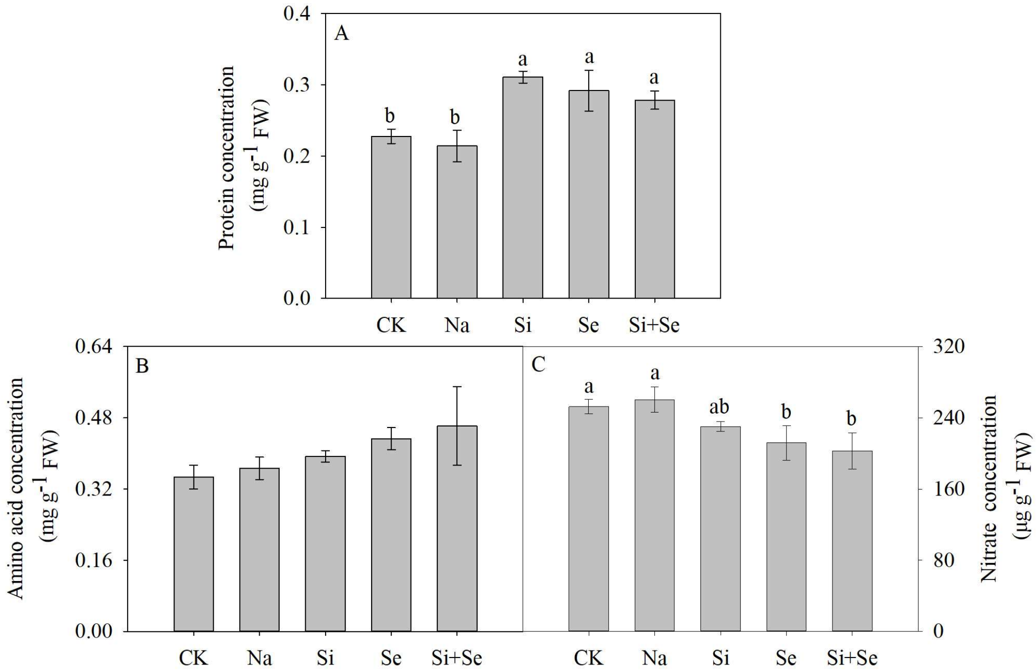

Figure 2. Effect of Si and Se on the concentrations of soluble protein (**A**), free amino acid (**B**) and nitrate (**C**) in tomato fruits. Data are shown as means ± SD (n = 4). Different letters above bars indicate significant differences among treatments ($p < 0.05$). CK, control (H_2O); Na, 1.0 mM Na_2SO_4; Si, 1.0 mM Na_2SiO_3 Se, 25 µM Na_2SeO_3 + 1.0 mM Na_2SO_4; Si + Se, 1.0 mM Na_2SiO_3 + 25 µM Na_2SeO_3.

3.7. Concentrations of Secondary Metabolites in the Fruit

In this study, we also investigated the effect of Si and Se on the levels of some secondary metabolites in the fruits, including vitamin C, total phenols, flavonoids, anthocyanin, lycopene, β-carotene and total carotenoids. The results showed that compared with the 'Na' treatment, spraying Si had no effect on the concentrations of these substances; Se application alone significantly increased the concentrations of vitamin C, total phenols, anthocyanin, lycopene and total carotenoids in the fruit, but it had no effect on the flavonoids concentration (Table 5). Compared with the 'Na' treatment, the combined application of Si and Se significantly increased the concentrations of total phenols and flavonoids (Table 5). Neither Si nor Se application affected the β-carotene in the fruit (Table 5).

Table 5. Effect of Si and Se on the concentrations of secondary metabolites in tomato fruits.

Treatment	Vitamin C ($\mu g\ g^{-1}$)	Total Phenols ($\mu g\ g^{-1}$)	Flavonoids ($\mu g\ g^{-1}$)	Anthocyanin ($nmol\ g^{-1}$)	Lycopene ($mg\ kg^{-1}$)	β-Carotene ($mg\ kg^{-1}$)	Total Carotenoids ($mg\ kg^{-1}$)
CK	134.0 ± 9.9 b	322.5 ± 14.1 c	88.0 ± 14.0 ab	11.6 ± 1.1 b	14.8 ± 1.8 b	7.43 ± 0.81	22.2 ± 1.3 b
Na	131.1 ± 17.4 b	335.7 ± 13.6 bc	76.6 ± 12.8 b	10.6 ± 0.8 b	15.7 ± 2.0 b	6.77 ± 0.52	22.4 ± 2.4 b
Si	141.3 ± 5.9 ab	351.0 ± 7.9 b	86.7 ± 9.7 ab	11.8 ± 0.4 b	17.0 ± 1.4 ab	6.70 ± 0.16	23.7 ± 1.5 b
Se	169.4 ± 26.2 a	384.2 ± 6.9 a	82.9 ± 8.3 b	14.2 ± 0.2 a	21.7 ± 3.3 a	7.85 ± 0.30	29.5 ± 3.0 a
Si + Se	159.2 ± 9.0 ab	390.1 ± 9.7 a	110.6 ± 15.1 a	11.6 ± 0.2 b	19.7 ± 0.5 ab	7.14 ± 0.14	26.9 ± 0.6 ab
F test	*	***	*	***	**	ns	**

Data are shown as means ± SD (n = 4). Values followed by different letters indicate significant differences among treatments ($p < 0.05$). CK, control (H_2O); Na, 1.0 mM Na_2SO_4; Si, 1.0 mM Na_2SiO_3; Se, 25 μM Na_2SeO_3 + 1.0 mM Na_2SO_4; Si + Se, 1.0 mM Na_2SiO_3 + 25 μM Na_2SeO_3. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$; ns, not significant at $p < 0.05$.

3.8. Comprehensive Evaluation of Plant Growth, Fruit Yield and Quality

The plant growth, yield and fruit quality were comprehensively evaluated by TOPSIS. The results showed that the Si + Se treatment obtained the highest score and thus was the optimal treatment, followed by the Se and Si treatments in turn (Table 6).

Table 6. Ranking and score of comprehensive evaluation of plant growth, fruit yield and quality evaluated by TOPSIS.

Treatment	D+	D−	CI	Ranking
CK	0.635	0.140	0.181	4
Na	0.704	0.048	0.064	5
Si	0.468	0.317	0.404	3
Se	0.215	0.587	0.732	2
Si + Se	0.149	0.664	0.817	1

D+, positive Euclidean distance; D−, negative Euclidean distance; CI, comprehensive evaluation index.

4. Discussion

The effect of Si application on tomato growth and yield has been reported in some studies [18–20,42]. In this study, we observed Si-mediated increases in the stem diameter, number of leaves and yield per plant, which confirmed the positive effect of Si on tomato growth and yield (Tables 1 and 2). Our results also demonstrated that the increased tomato yield resulting from added Si was attributable to the slight increase in fruit number, which coincides with the observations by Toresano-Sanchez et al. [43] and Gao and Cao [19]. However, our result that Si addition did not affect the single fruit weight is inconsistent with the observations by Xue et al. [18] and Gao and Cao [19]. The reason for these differential effects of Si is not clear, but may be associated with the Si application modes and/or tomato genotypes.

There have been some studies on the effect of Se on tomato growth and yield. For instance, Chen and Xue [44] reported that root application of nano-Se promoted the dry mass contents of shoot and roots. Neysanian et al. [33] observed that foliar spraying of suitable nano-Se and sodium selenate levels increased the shoot and root fresh weights. In this study, we also observed the positive effect of Se on tomato growth, as demonstrated by the increases in the plant height and stem diameter (Table 1). However, Liu et al. [32] found that spraying sodium selenite had little effect on tomato growth. These studies may suggest that the effect of Se on tomato growth is dependent on the genotype used. In this study, we also found that the foliar addition of Se had no significant effect on the single fruit weight, the fruit number or yield per plant (Table 2). Our results are consistent with the observations by Liu et al. [32] in 'Chunfa 78'. However, the positive effect of Se on tomato yield has been reported in other studies. For instance, Hernandez-Hernandez et al. [1] observed that root application of Se nanoparticles at 10 mg L^{-1} increased the number of fruits and thus the yield per plant. Neysanian et al. [33] found that the fruit number and fruit fresh weight were significantly increased by spraying 3 mg L^{-1} sodium selenate or Se nanoparticles. Sabatino et al. [45] also found that Se application increased the fruit number and marketable yield of cherry tomato in soilless culture, although the average fruit weight was decreased. These studies suggest that the effects of Se on tomato yield are associated with the Se application method, Se source type or tomato cultivar.

Although the effect of combined Si and Se treatment on the growth and yield have been reported in some crops, including orange [34], mango [35], rice [13] and cucumber [17], to our knowledge, little information is available on tomato. In this study, we observed that the combined Si and Se treatment did not further improve the tomato growth or yield compared with either single application (Tables 1 and 2). Our results coincide with the observation of the rice 'Yuxiangyouzhan' by Liu et al. [13], who reported that the combined application of Si and Se did not have a superior effect on the grain yield or head rice yield to that of their individual applications in a field experiment. In contrast to these, Ahmed et al. [35] and Hu et al. [17] observed that the combined Si and Se treatment resulted in better improvement in the yield than the single treatments in mango and cucumber, respectively. These studies suggest that the effect of combined Si and Se application is dependent on plant species. Despite the fact that no superior effect was observed in this study, our results demonstrated that the combined treatment of Si and Se resulted in both the effects of Si-mediated yield increase and Se-mediated fruit quality improvement, suggesting that the combined application is an alternative strategy to improve the yield and quality in tomato production.

Foliar spraying is a simple and feasible approach to increase the concentrations of Si and Se in the edible parts of crops [46–49]. In tomato, Jarosz [50] reported that the addition of Si to the nutrient solution did not change the concentration of this element in the fruit, and Kleiber et al. [51] found that the fruit Si concentration varied depending on the nutrient intensity and the year. These studies suggest that growth medium is an important factor affecting Si accumulation in the fruit, as Jarosz [50] previously pointed out. In this study, we found that the foliar application of Si did not change its level in the tomato fruits (Figure 1A), which is consistent with the results of Jarosz [50]. However, it should be noted that Si was added by foliar application in our work, but not root application, as in previous studies [50,51]. In the future, it would be interesting to investigate the mechanism of Si translocation in tomato. The increase of Se in tomato fruits by Se application has been frequently reported [23,52,53], and our results are consistent with the observations in these studies (Figure 1B), suggesting the feasibility of foliar application in increasing the fruit Se level, an important quality trait in tomato.

The concentrations and components of carbohydrates have an impact on the flavor quality of tomato [54]. There has been limited literature about the effect of Si application on the carbohydrate concentrations in tomato. Xue et al. [18] and Jalali et al. [20] have respectively found that the concentrations of soluble sugars and total carbohydrates in tomato fruits were increased by added Si, and they did not analyze the levels of individual sugar components. In this study, we observed that Si application slightly increased the total carbohydrate level in the fruit by enhancing the sucrose concentration, which confirms the positive role of Si in promoting carbohydrate accumulation in tomato. The effect of applied Se on the carbohydrate levels in tomato fruits has also been reported in some studies, but with different results. For instance, Li et al. [55] and Liu et al. [32] observed an increase in the total soluble sugar concentration in the fruit from the application of sodium selenate and sodium selenite. Zhu et al. [2] found that foliar application of sodium selenate increased the levels of both glucose and fructose in tomato fruits. However, Puccinelli et al. [56] did not observe any difference in the levels of glucose or fructose in the fruit after application of sodium selenate. Jalali et al. [20] reported that spraying sodium selenite did not affect the concentration of total carbohydrates, either. In this study, Se spray increased the levels of different soluble sugars in the fruit (Table 3). These studies imply the complex effect of Se on the carbohydrate levels in tomato fruits, and the observed differential effects may be associated the cultivars used. In addition, to our knowledge, the combined effect of Si and Se on the accumulation of carbohydrates in tomato fruits has not been investigated. In this study, we found that although the combined Si and Se treatment increased the concentrations of soluble sugars, it did not show any superior effect to that of either individual applications, which is in contrast to the observations in mango [35] and orange [34]. These studies suggest that the superior effect of the combined treatment is dependent on plant species. Previously, we found that the Si- and Se-mediated increases in soluble sugar levels in cucumber fruit may be attributed to the increased activities of sucrose metabolism related enzymes [17]. The effects of Si and Se on activities of these enzymes in tomato remain to be investigated in future.

The levels of organic acids also affect the flavor quality of tomato [57]. There has been some literature regarding the effect of the individual application of Si or Se on the organic acid level in tomato fruits, and differential effects were observed. For example, Xue et al. [18] reported that spraying two different forms of Si reduced the total titratable acidity of tomato fruits, whereas Jalali et al. [20] observed an increase in the total titratable acidity in tomato by added Si. Jalali et al. [20] and Liu et al. [32] observed that foliar spraying of sodium selenite increased the total titratable acidity of the fruit, whereas Meucci et al. [58] observed that foliar spraying of sodium selenate at the flowering period decreased the titratable acidity. In addition, Puccinelli et al. [56] reported that a sodium selenate addition did not change the titratable acidity. Similarly, Zhu et al. [2] found that foliar spraying of sodium selenate did not affect the concentrations of citric acid and malic acid in tomato. As of this writing, little information is available about the effect of Si or Se on the levels of individual organic acid components in tomato fruits. Moreover, the combined effect of these elements on the organic acid concentration is unclear. In this study, we found that Si and Se application, whether separately or in combination, did not alter the concentrations of individual or total organic acids in tomato fruits. These studies suggest that the effects of Si or Se on the levels of organic acids may be associated with tomato cultivars, Se sources and/or application modes.

Proteins and amino acids are important nitrogen-containing substances in fruits. The effects of the addition of Si and Se on protein and amino acid concentrations have been reported in tomato fruits with differential results. Cao et al. [59] found that Si application increased the levels of soluble protein and free amino acids in the fruit under alternate wetting and drying conditions. Zhao et al. [21] observed that the foliar application of Si significantly increased the concentration of free amino acid, but did not change the soluble protein level in the cultivar 'Xin Yan Xiabao'. With regard to the effect of Se, Han et al. [60] observed that the application of sodium selenate increased the soluble protein concentration in the cultivar 'Xiariyangguang', but did not change the concentration in 'Yali 616', while sodium selenite application did not show any effect on the soluble protein level in either cultivar. Zhu et al. [2] found that Se application increased the levels of some essential and nonessential amino acids in the fruit. In this study, we observed that foliar application of Si and Se increased the concentration of soluble protein but not free amino acid in the fruit (Figure 2A,B). Our results, together with previous studies, suggest that the effect of Si and Se on soluble protein levels is dependent on the cultivar, and the Se's effect may also be associated with the Se source.

Nitrate level is an index indicating the safety quality of vegetables [17]. Very limited information is available on the effect of Si application on nitrate accumulation in the tomato fruit. Xue et al. [18] reported that the application of both inorganic and organic Si significantly decreased the nitrate concentration in the fruit. Our result in this study is inconsistent with the observation by Xue et al. [18]. As far as the authors are aware, the effect of Se on the nitrate concentration in tomato fruits has rarely been reported. In this study, we found that compared with either control, spraying Se separately or in combination with Si both significantly reduced the nitrate level in the fruit (Figure 2C).

These studies suggest that Se addition could improve the safety quality of tomato fruits. The mechanism for a Se-mediated decrease in nitrate levels in tomato remains to be studied, and it may be related to an increased nitrate reduction ability, as observed in cucumber in our previous work [17].

Secondary metabolites are closely related to human health. To our knowledge, at present, there has been very limited literature produced about the effect of added Si on the levels of vitamin C, phenols, flavonoids, lycopene or β-carotene in tomato fruits. In this study, we found that foliar application of Si did not affect the concentrations of these secondary metabolites. Our results regarding the lycopene and β-carotene concentrations are in accordance with those of Costan et al. [22] and Zhao et al. [21], whereas other results are inconsistent with their observations: Zhao et al. [21] observed Si-mediated increases in the concentrations of vitamin C, phenols and flavonoids in the fruit, and Costan et al. [22] found that added Si decreased the vitamin C level, but did not affect the concentration of phenols in a hydroponic system. These studies suggest that the effect of Si on the concentrations of secondary metabolites may be dependent on the tomato cultivars. There have been plenty of studies on the effect of Se on the levels of secondary metabolites in tomato fruits, and most of them were focused on vitamin C, and to a lesser extent on lycopene. The Se-mediated increase in the vitamin C level observed in this work is in accordance with that found in most previous studies [2,23,56,61], but is inconsistent with that of Hernández-Hernández et al. [1] and Liu et al. [32], who did not observe any effect of Se on the vitamin C level, suggesting a difference among cultivars. In this study, the positive effect of Se on the lycopene concentration coincides with that described by Shao et al. [61], who also used sodium selenite as the Se source. However, no effect of Se on the lycopene level was observed in several studies where selenate or nano-Se was applied [1,2,23,56]. These seem to suggest that the effect of Se on the lycopene concentration is related to the Se source. Differential changes in the levels of total phenols and flavonoids as a result of added Se have also been observed in this work and previous studies [1,2,23], and the reason for this is unclear. To our knowledge, little information is available on the effect of Si and Se application on the anthocyanin concentration in tomato fruits, and our results showed that application of Se alone, but not Si, enhanced the anthocyanin concentration in the fruit (Table 5). More work is needed to repeat this experiment in different cultivars. Up to date, the combined effects of Si and Se on the levels of secondary metabolites in tomato fruits are still unknown. In this work, we did not observe any superior effect of the combined treatment on the concentrations of secondary metabolites. In summary, the increased levels of secondary metabolites by Se application contribute to the improvement of tomato quality. In future, it would be interesting to study the mechanism for Se-mediated increases in the secondary metabolites concentrations.

5. Conclusions

Both Si and Se application improve the growth of tomato plants. Si application increases the tomato yield, while Se application improves the fruit quality. The combined Si and Se treatment has positive effects on both yield increase and quality improvement. The study may provide basic knowledge about the possibility of application of Se and Si fertilizers in tomato production.

Author Contributions: Investigation, methodology, data curation, formal analysis and writing—original draft, W.H.; investigation, Y.S., R.Y. and Z.X.; conceptualization, funding acquisition and writing—review and editing, H.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the National Natural Science Foundation of China (32072561) and the Shaanxi Provincial Key Research and Development Plan of China (2019TSLNY01-02).

Data Availability Statement: The data used and presented in this paper are available upon request from the corresponding authors.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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