Technology in Horticulture

ARTICLE

Open Access

https://doi.org/10.48130/TIH-2022-0005

Technology in Horticulture **2022**, 2:5

Impact of nutrient solutions under inorganic substrate soilless cultivation on plant growth, fruit yield and quality of tomato

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Abstract

Soilless cultivation has been widely used in tomato (*Solanum lycopersicum*) production. The objectives of this research are to evaluate the impacts of five nutrient solutions under soilless cultivation on plant growth, fruit yield and fruit quality in tomatoes. Four experiments were conducted with six treatments (five nutrient solutions plus one control) in six-cherry tomato cultivars and two big fruited tomato cultivars and 12 traits were observed and evaluated. The results showed that each of the five solutions increased plant growth and fruit yield, and improved the fruit quality. Compared to the control, the nutrient solution treatments increased 91.3% for number of fruits on base fruit cluster, 12.1% for height, and 26.3% for stem diameter in the 2017-experiment; 17.1% for vitamin C, 13.8% for soluble solids, and 20.8% for total soluble sugar content in 2018-experiment one; 28.1% for number of fruit cluster, 25.8% for fruit yield, 9.4% for number of fruit per cluster, and 13.3% for single fruit weight in 2018-experiment two; and 27.7% for vitamin C, 14.0% for soluble solids, 18.1% for total soluble sugar content, and 14.6% for fruit yield in the 2019-experiment. The solution decreased the chemical nitrate content 16.2% in the 2018-experiment and 43.7% in the 2019-experiment, and decreased the fruit cracking rate by 87%. Treatment 2 with higher nutrient component content showed the best results of the five treatments. The significant high positive correlation among the beneficial traits, fruit yield, soluble solids, total soluble sugar content, and vitamin C, and high negative correlation between each of the four traits and nitrate content were observed, indicating that soilless cultivation can increase tomato yield with higher nutritional components and decreased nitrate content. This research provides useful information for utilizing nutrient solutions supplied to tomato soilless cultivation.

Citation: Guo J, Jiao Y, Xiong H, Shi A, Yang Y, et al. 2022. Impact of nutrient solutions under inorganic substrate soilless cultivation on plant growth, fruit yield and quality of tomato. *Technology in Horticulture* 2:5 https://doi.org/10.48130/TIH-2022-0005

INTRODUCTION

Tomato (*Solanum lycopersicum* L.) is a highly nutritional vegetable crop, cultivated worldwide, and its production and consumption continue to increase[1]. As commercial tomato cultivars require large amounts of water and high quality fertilizers, farmers are suffering reduced fruit qualities and yields in the areas with a shortage of appropriate climate and field management[2,3].

In recent years, the soilless production of greenhouse tomatoes has increased dramatically[4]. Soilless production systems can control fertilizers and irrigation more effectively, resulting in higher yield and quality[5]. In soilless cultivation, the plant roots may grow either in porous media (substrates), or directly in a nutrient solution without any solid phase[6]. In addition, soilless cultivation can significantly reduce pathological problems; avoid contamination of soil; and reduce accumulation of nitrates (NO_3^-) and pesticides, thereby promoting sustainable agriculture practices[7]. The accumulation of NO_3^- was considered to be a crucial factor in reducing the edible qualities of some vegetables. In countries with environmental legislation, over the past decade, the use of these systems has been encouraged in order to minimize damage to natural ecosystems caused by excessive use of chemical fertilizers[8].

There are two main challenges in soilless tomato cultivation, (1) tomato is considered moderately sensitive to salinity (nutrient solution), and (2) its production cycle is long, and the nutrient requirements vary greatly in different growth stages[9]. A high level of nutrients improves fruit quality, such as the total soluble solids and antioxidant compounds, however, some researchers reported that when electrical conductivity (EC) of nutrient solution exceeds 2.5–4.0 $ds{\cdot}m^{-1}$, the growth and yield of the crop begin to decline[10]. One of the effects of nutrient solution on plants is the 'osmotic effect' because plants' roots are exposed to excessive salt in the growing medium, limiting the absorbtion of water, causing water loss in the body of the plant, and negatively affecting plant growth[11]. As the time of salt exposure increases, plants begin to experience phytotoxicity due to the accumulation of saline ions, as well as nutrient imbalance (inhibition of absorption of certain nutrients). These factors will negatively affect the physiological and metabolic processes of plants, such as photosynthesis, respiration, and cell division which could lead to the synthesis of reactive oxygen species, ultimately leading to reduced vegetative growth and yield[12]. To explore the appropriate nutrient solution at each growth stage to balance yield and quality is of great significance to tomato production. At present, there are relatively few studies on the supply of different concentrations of nutrient solutions according to the growth period. Therefore, choosing the right nutrient solution formula and the best concentration for different growth periods are very important in order to promote crops' growth and development and increase yield and quality [13].

In this study, four experiments from 2017 to 2019 were conducted for eight tomato cultivars, including six cherry tomato and two big-fruited tomato cultivars, and five treatments with five pairs of nutrient solutions were applied to this practical tomato production. The objectives of this research were to evaluate the impact of nutrient solutions under inorganic substrate soilless cultivation on plant growth, fruit yield, and fruit quality in order to provide useful information for soilless tomato cultivation.

RESULTS

Evaluation of plant growth, fruit yield, and fruit quality under soilless cultivation

The plant growth, fruit yield, and fruit quality under soilless cultivation were observed and measured in the four experiments (Supplemental Table S1).

In the 2017 experiment, plant height, stem diameter, and number of fruits on the base cluster were observed among five cherry tomato cultivars. Number of fruits on the base cluster among the five cultivars, ranged from 1.5 to 5.8, and averaged 3.8; the standard deviation (SD) was 0.96 with standard error (SE) 0.10; and the coefficient of variation (CV) was 24.9%, indicating there were significant genetic differences of the number of fruit on the base cluster among the five cultivars (Supplemental Table S1). Plant height, ranged from 55.1 to 80.1 cm, and averaged 68.2 cm; the SD was 6.60 with SE 0.70; and the CV was 9.67 (Supplemental Table S1), indicating that there were significant genetic differences of plant height among the five cultivars. Stem diameter, ranged from 7.2 to 15.5 mm, and averaged 11.2 mm; and the CV was 18.48 (Supplemental Table S1), indicating that there were significant difference of the stem diameter among the five cultivars. Correlation among the three traits were observed and the results showed that there were significant positive correlation between the number of fruit on the base cluster and height (correlation coefficient (r) = 0.31) and between the number of fruit on the base cluster and stem diameter (r = 0.52), but there was no significant correlation between plant height and stem diameter (r = −0.03) (Supplemental Table S2), indicating that the taller tomato cultivar had more fruit on the base cluster and more fruit on the base cluster had wider stems.

In the 2018 experiment one, four chemical traits, vitamin C, soluble solids, total soluble sugar content, and nitrate content were observed and measured in three cherry tomato cultivars. Vitamin C content, ranged from 22.0 to 31.6 mg/100g, and averaged 27.5 mg/100g; the SD was 2.49 with SE 0.34; and the CV was 9.05 (Supplemental Table S1); indicating that there were significant genetic differences of vitamin C content among the three cultivars. Soluble solids, ranged from 6.0% to 8.7%, and averaged 7.0%; the SD was 0.56 with SE 0.08; and the CV was 7.95 (Supplemental Table S1); indicating that there were significant genetic differences of soluble solid content among the three cultivars. Total soluble sugar content, ranged from 39.0 to 57.6 mg/g, and averaged 49.7 mg/g; the SD was 5.33 with SE 0.73; and the CV was 10.74 (Supplementary Table S1); indicating that there were significant genetic differences of the total soluble sugar content among the three cultivars. Nitrate content, rangied from 65.4 to 127.7 mg/kg, and averaged 100.6 mg/kg; the SD was 15.79 with SE 2.15; and the CV was 15.70 (Supplemental Table S1); indicating that there were significant genetic differences of nitrate content in the three cultivars. Correlation among the four chemical traits were observed and the results showed that there was significant positive correlation between vitamin C and soluble solids (r = 0.55), between vitamin C and total soluble sugar content (r = 0.85), and between soluble solids and total soluble sugar content (r = 0.62) (Supplemental Table S2), indicating that we can select tomato with high vitamin C, high soluble solids, and high total soluble sugar content, simultaneously. High negative correlations were observed between nitrate content with three other chemical components, vitamin C (r = −0.46), soluble solids (r = −0.51), and total soluble sugar content (r = −0.66) (Supplemental Table S2), indicating that we can increase the three nutrients and decrease the nitrate content, simultaneously.

In the 2018 experiment two, five physiological traits, ear number, fruit cracking rate, number of fruits per cluster, single fruit weight, and fruit yield were observed and measured in four cherry tomato cultivars. All five traits showed that there were significant differences among the four cherry tomato cultivars with a high CV value of 32.13%, 12.63%, 32.56%, 9.89%, and 178.85% for fruit yield, single fruit weight, number of fruits per cluster, number of fruit cluster, and fruit cracking rate, respectively (Supplemental Table S1), indicating that there were significant genetic differences among these traits. The correlations among the five traits were observed and the results showed that there was a strong positive correlation between fruit yield and number of fruits per cluster (r = 0.86) and a low significant positive correlation between fruit yield and number of fruits cluster (r = 0.31) and no significant correlation between fruit yield and single fruit weight (r = 0.20, probability value (*P*) = 0.098) or fruit cracking rate (r = −0.02, *P* = 0.867) (Supplemental Table S2), indicating that number of fruits per cluster was the major factor determining high fruit yield. There was a positive correlation between single fruit weight and number of fruits in a cluster (r = 0.46), indicating that we can select both higher number of fruit clusters and larger fruits in the same cherry tomato cultivars. The fruit cracking rate had a strong negative correlation with single fruit weight (r = −0.51) or number of fruit clusters (r = −0.56), but positive correlation with number of fruits per cluster (r = 0.31) and no significance with fruit yield (r = −0.02, *P* = 0.867) (Supplemental Table S2), indicating that the higher number of fruits per cluster can increase the fruit cracking rate in cherry tomato.

In the 2019 experiment, five traits, vitamin C, fruit yield, soluble solids, total soluble sugar, and nitrate content were observed and measured in two large big-fruited tomato cultivars. All five traits showed differences between the two cultivars with a high CV value of 11.32%, 6.04%, 7.83%, 10.65% and 31.33% for vitamin C, fruit yield, soluble solids, total soluble sugar content, and nitrate content, respectively (Supplemental Table S1), indicating that there were significant genetic differences among these traits. The correlations between the five traits were observed and the results showed that there were strong positive correlations between vitamin C, fruit yield, soluble solids, and total soluble sugar content (r > 0.4) with six combinations (Supplemental Table S2), indicating that the fruit yield and the nutrient components are associated. The correlation among the three nutrients in the two big-fruited tomato cultivars in the 2019 experiment were similar to those in the 2018 experiment one for cherry tomatoes. The nitrate content was strongly and negatively correlated with soluble solids (r = −0.73) or total soluble sugar content (r = −0.60), and weakly and negatively correlated with vitamin C (r = −0.24) or fruit yield (r = −0.16) (Supplemental Table S2), indicating that the higher nutritional components or high yield will decrease the nitrate content in big fruited tomato similar to those in cherry tomato.

Analysis of Variance (ANOVA) for each trait was analyzed in the four experiments, respectively, and the results are listed in Supplemental Table S3. In the 2017 experiment, both 'Cultivar' and 'Treatment' were significantly different in the number of fruit on the base cluster, height, and stem diameter ($P \leq 0.0005$) (Supplemental Table S3), indicating that there were significant differences among the five cherry tomato cultivars for the three traits, and there were significant treatment differences in the three traits, no significant interaction between cultivar and treatment was observed ($P > 0.05$).

In the 2018 experiment one, both 'Cultivar' and 'Treatment' were significantly different for the three traits, vitamin C, total soluble sugar, and nitrate content ($P < 0.0001$), but less significant for soluble solids ($P < 0.01$) in the three cherry tomato cultivars (Supplemental Table S3), indicating that there were significant differences among three cherry tomato for the four traits, and there were significant differences among the six treatments. No significant interaction between 'Cultivar × Treatment' was observed ($P > 0.05$) for the three traits except nitrate content ($P = 0.0005$).

In the 2018 experiment two, 'Cultivar', 'Treatment', and "Cultivar × Treatment" were all significantly different for the three traits, fruit yield, single fruit weight, and fruit cracking rate ($P < 0.0001$), indicating that there were significant differences among the four cherry tomato for the three traits; there were significant differences among the six treatments; and there were also interactions ($P < 0.0001$) (Supplemental Table S3). However, there were less significant difference for number of fruits per cluster among the six treatments ($P = 0.0227$); no significant differences for number of fruit clusters among the four cultivars ($P = 0.349$); no interaction between 'Cultivar x Treatment' for number of fruits per cluster ($P = 0.0746$) and for the number of fruit clusters ($P = 0.9862$).

In the 2019 experiment, there were no significant differences for 'Cultivar' (i.e. between the two cultivars, Jinpeng 11 and Fengshouhuang) for fruit yield ($P = 0.3285$), for soluble solids ($P = 0.3903$), and for total soluble sugar content ($P = 0.0759$), there were significant differences for five traits, vitamin C, fruit yield, soluble solids, total soluble sugar content, and nitrate content between the two cultivars and there were significant differences among the six treatments with $P < 0.05$ (Supplemental Table S3) interactions were also observed.

Effect of nutrient solutions on plant growth, fruit yield and quality

In this study, there were six treatments (T1 to T6): five nutrient solutions applied to soilless cultivation and one control applied to the soil-based cultivation with regular irrigation and fertilization to study how the nutrient solutions affect plant growth, fruit yield, and fruit quality. Four experiments were conducted for the six treatments with six cherry tomato cultivars and two big fruited tomato cultivars and 12 traits were observed (Table 1).

In the 2017 experiment, all five treatments from T1 to T5 had significantly higher values than the control (T6) for all three traits; increasing 69.6% of T1 to 91.3% of T2 for the number of fruit on the base cluster; 8.8% in T1 to 12.1% in T2 for height; 6.1% in T1 to 26.3% in T2 for stem diameter, respectively (Table 1, Supplemental Fig. S1), indicating that each of the five solutions increased the number of fruit on the base cluster, height and stem diameter. The T2 solution resulted in the highest for each of the three traits (Table 1, Supplemental Fig. S1), indicating that T2 was the best from the 2017 experiment.

In the 2018 experiment one, all five treatments from T1 to T5 had significantly higher values than the control (T6) for three nutritional components, vitamin C, soluble solids, and total soluble sugar content, but significantly lower than the control for nitrate content; increasing 11.8% of T5 to 17.1% of T2 for vitamin C; 6.2% in T1 to 13.8% in T2 for soluble solids; 15.5% in T5 to 20.8% in T2 for total soluble sugar content; −20.4% in T1 and −16.2% in T2 for nitrate content, respectively (Table 1, Supplemental Fig. S2), indicating that each of the five solutions increased the three nutritional components, vitamin C, soluble solids, and total soluble sugar content, and decreased nitrate content. The T2 solution was the highest for each of the three nutrients and the T1 solution decreased the most but there were no significant differences among the five nutrient solutions for nitrate content, indicating that T2 was the best from the 2018 experiment one.

In the 2018 experiment two, all five treatments from T1 to T5 had significantly higher values than the control (T6) for the number of fruit cluster, fruit yield, number of fruits per cluster, and single fruit weight, but significantly lower than the control for fruit cracking rate, which is a disadvantageous trait for tomato production. T1, T3, and T5 were higher but not significantly than the control; increasing 20.3% of T1 (= T5) to 28.1% of T2 for number of fruit cluster; 24.3% in T1 to 25.8% in T2 for fruit yield; 2.1% in T1 to 9.4% in T2 for number of fruit per cluster; 7.0% in T1 to 13.3% in T2 for single fruit weight; −94.4% in T1 to −83.3% in T4 for fruit cracking rate, respectively (Table 1, Supplemental Fig. S3), indicating that each of the five solutions increased the number of fruit cluster, fruit yield, number of fruits per cluster, and single fruit weight, but decreased the disadvantageous fruit cracking rate. The T2 solution was the highest for each of the four beneficial traits and the T1 solution decreased the most but there were no significant differences among the five nutrient solutions for fruit cracking rate, indicating that T2 was the best from the 2018 experiment two.

In the 2019 experiment, all five treatments from T1 to T5 had significantly higher values than the control (T6) for the three nutritional components, vitamin C, soluble solids, and total soluble sugar content, and also for fruit yield, but significantly lower than the control for nitrate content, with the exception of T3, T4, and T5 of soluble solids which were higher than or equal to T6 without significant differences; increasing 18.9% of T1 to 27.7% of T2 for vitamin C; 0% in T3 to 14.0% in T2 for soluble solids; 13.7% in T1 to 18.1% in T2 for total soluble sugar content; 2.5% in T5 to 14.6% in T2 (or T1) for fruit yield; −45.2% in T5 to −43.7% in T2 for nitrate content, respectively (Table 1, Supplemental Fig. S4), indicating that each of the five solutions

Table 1. Comparison of tomato traits affected by five treatments (T1 to T5) of nutrient components for soilless cultivation and the control (T6) for soil cultivation.

Trait		T1	T2	T3	T4	T5	T6 - soil as control	Experiment
Number of fruit on the base cluster	LSM*	3.9b** ± 0.19	4.4a ± 0.17	4.1ab ± 0.17	4.2ab ± 0.16	4.0b ± 0.18	2.3c ± 0.14	2017
	Incease%[c]	69.6***	91.3	78.3	82.6	73.9		
Height (cm)	LSM	68.3c ± 1.60	70.4a ± 1.74	69.0bc ± 1.60	70.0ab ± 1.73	68.6c ± 1.62	62.8d ± 1.39	
	Incease%	8.8	12.1	9.9	11.5	9.2		
Stem diameter (mm)	LSM	10.5cd ± 0.51	12.5a ± 0.53	11.4bc ± 0.47	11.8ab ± 0.54	11.1bc ± 0.50	9.9d ± 0.46	
	Incease%	6.1	26.3	15.2	19.2	12.1		
Vitamin C (mg/100g)	LSM	27.7ab ± 0.73	28.7a ± 0.66	28.0ab ± 0.68	28.4ab ± 0.72	27.4b ± 0.63	24.5c ± 0.84	2018 one
	Incease%	13.1	17.1	14.3	15.9	11.8		
Soluble solids (%)	LSM	6.9b ± 0.10	7.4a ± 0.22	7.0ab ± 0.21	7.2ab ± 0.16	7.0b ± 0.20	6.5c ± 0.12	
	Incease%	6.2	13.8	7.7	10.8	7.7		
Total soluble sugar content (mg/g)	LSM	50.5ab ± 1.45	52.2a ±1.65	50.7ab ± 1.55	51.5ab ± 1.74	49.9b ± 1.50	43.2c ± 1.01	
	Incease%	16.9	20.8	17.4	19.2	15.5		
Nitrate content (mg/kg)	LSM	94.1b ± 6.20	99.0b ± 4.85	97.3b ± 4.92	97.7b ± 5.40	97.0b ± 4.60	118.2a ± 2.93	
	Incease%	−20.4	−16.2	−17.7	−17.3	−17.9		
Number of fruit clusters	LSM	7.7b ± 1.82	8.2a ± 1.87	7.8b ± 1.87	8.0ab ± 1.89	1.86 ± 1.86	6.4c ± 2.26	2018 two
	Incease%	20.3	28.1	21.9	25.0	20.3		
Fruit yield (kg/667m^2)	LSM	5,177.4a ± 493.52	5,239.2a ± 497.37	5,197.4a ± 496.82	5,212.6a ± 494.75	5,184.2a ± 492.28	4,163.8b ± 312.27	
	Incease%	24.3	25.8	24.8	25.2	24.5		
Number of fruits per cluster	LSM	19.5bc ± 0.18	20.9a ± 0.16	19.9abc ± 0.13	20.5ab ± 0.15	19.7abc ± 0.13	19.1c ± 0.12	
	Incease%	2.1	9.4	4.2	7.3	3.1		
Single fruit weight (g)	LSM	15.3a ± 0.51	16.2a ± 0.50	15.8a ± 0.56	15.8a ± 0.45	15.5a ± 0.51	14.3b ± 0.74	
	Incease%	7.0	13.3	10.5	10.5	8.4		
Fruit cracking rate (%)	LSM	0.3b ± 0.16	0.7b ± 0.26	0.7b ± 0.23	0.9b ± 0.25	0.7b ± 0.21	5.4a ± 1.29	
	Incease%	−94.4	−87.0	−87.0	−83.3	−87.0		
Vitamin C (mg/100g)	LSM	18.9a ± 0.59	20.3a ± 0.52	19.3a ± 0.54	19.7a ± 0.59	19.0a ± 0.54	15.9b ± 1.19	2019
	Incease%	18.9	27.7	21.4	23.9	19.5		
Soluble solids (%)	LSM	6.3a ± 0.09	6.5a ± 0.22	5.7b ± 0.17	5.9b ± 0.16	5.9b ± 0.16	5.7b ± 0.12	
	Incease%	10.5	14.0	0.0	3.5	3.5		
Total soluble sugar content (mg/g)	LSM	40.5a ± 1.67	42.0a ± 1.87	40.8a ± 1.78	41.6a ± 1.87	40.5a ± 1.69	35.6b ± 0.26	
	Incease%	13.7	18.1	14.6	17.0	13.9		
Fruit yield (kg/667m^2)	LSM	6,664.7a ± 155.79	6,663.2a ± 154.10	6,580.0a ± 170.30	5,985.3b ± 150.85	5,958.7b ± 157.21	5,816.2c ± 187.86	
	Incease%	14.6	14.6	13.1	2.9	2.5		
Nitrate content (mg/kg)	LSM	357.4b ± 14.68	362.9b ± 14.47	354.4b ± 16.34	359.0b ± 14.36	352.9b ± 13.07	644.5a ± 63.00	
	increase%	−44.5	−43.7	−45.0	−44.3	−45.2		

* LSM = least squared mean for each trait in each of the six treatments and standardize error
** significant at $P = 0.05$ level in raw.
*** Increase% = percentage increase for each of the five nutrient solutions from T1 to T6 compared to the control (T6) = 100 × (Tn − T6)/T6, such as for 'Number fruit first era' in T1 treatment of the 2017 experiment = 100 × (T1 − T6)/T6 = 100 × (3.9 − 2.3)/2.3 = 69.6%

increased the three nutritional components, vitamin C, soluble solids, and total soluble sugar content and increased the fruit yield but decreased nitrate content. The T2 solution was the highest for each of the three nutrients and for fruit yield and the T5 solution decreased the highest but there were no significant differences among the five nutrient solutions for nitrate content, indicating that T2 was the best from the 2019 experiment.

Comparisons between soilless and soil cultivation

Comparisons of physiological and chemical traits between soilless and soil-based cultivations were analyzed by average (Table 2) and by each tomato cultivar, respectively (Table 3). In the 2017 experiment, soilless with nutrient solution cultivation was higher than soil-based cultivation for the three traits: increasing 79.1% for number of fruits on the base cluster; 10.3% for height; and 15.8% for stem diameter. For each of the five cherry tomato cultivars, the soilless cultivation increased 82.6% in Xiariyangguang to 141.2% in Fenyuan for the number of fruits per cluster; 6.1% in Hongyu to 16.2% in Ziyu for plant height; 18.1% in Yuanwei NO.1 to 34.2% in Xiariyangguang for stem diameter (Table 3), indicating the nutrient solutions on the soilless cultivation increased number of fruit per cluster, plant height and stem diameter in each of the five tomato cultivars.

In the 2018 experiment one, soilless with the five nutrient solution cultivation was higher than soil-based cultivation for the three nutritional traits: increasing 14.4% for vitamin C; 9.2% for soluble solids, 18.0% for total soluble sugar content; and −17.9% for nitrate content (Table 2), indicating the nutrient solutions increased the three nutritional components, but decreased nitrate content. The soilless cultivation showed better results in each of the four cherry tomato cultivars; increasing 10.7% in Xiariyangguang to 26.7% in Fenyuan for vitamin C; 9.5% in Xiariyangguang to 21.0% in Hongyu for soluble solids; 11.6% in Hongyu to 24.8% in Xiariyangguang for total soluble sugar; −9.6% in Xiariyangguang (or Huangzhenzhu) to −29.9% in Fenyuan (Table 3), indicating the nutrient solutions increased the three nutritional components, but decreased nitrate content in each of the four cherry tomato cultivars.

In the 2018 experiment two, soilless with the five nutrient solution cultivation was higher than soil-based cultivation for the four benefit traits, number of fruit cluster, fruit yield, fruit weight, and number of fruits per cluster increased 23.1% for number of fruit cluster; 24.9% for fruit yield; 5.2% for number of fruits per cluster; 9.9% for single fruit weight; and −87.8% for fruit cracking rate (Table 2). The soilless cultivation performed better in each of the four cherry tomato cultivars except number of fruit per cluster in Xiariyangguang, but decreased for the disadvantageous fruit cracking trait; increasing 20.6% in Fenyuan to 38.3% in Xiariyangguang for number of fruit per cluster; 2.6% in Huangzhenzhu to 50.9% in Xiariyangguang for fruit yield; 0.6% in Fenyuan to 52.7% in Xiariyangguang for fruit weight; −2.3% in Xiariyangguang to 29.8% in Hongyu; 0% in Hongyu to −93.6% in Huangzhenzhu for fruit cracking (Table 3), indicating the nutrient solutions on the soilless cultivation increased number of fruit cluster, fruit yield, fruit weight, and number of fruit per cluster and decreased the fruit cracking rate in the four cherry tomato cultivars or each cultivar, respectively.

In the 2019 experiment, soilless with the five nutrient solution cultivation was higher than soil-based cultivation for the three nutritional components, vitamin C, soluble solids, and total soluble sugar content, and for fruit yield, but lower than soil-based cultivar for nitrate content in the two cultivars on average (Table 2), or by each cultivar, respectively (Table 3), indicating that the nutrient solutions in soilless cultivation increased the vitamin C, soluble solids, total soluble sugar content, and fruit yield, but decreased nitrate content in the two big fruited tomato cultivars on average or individually.

Cultivar and nutrient solution interaction

Cultivar and nutrient solution interactions were observed although the majority of results in this study was not significantly different for most traits in the four experiments (Supplemental Table S3). The comparisons of Cultivar x Treatment interactions in each trait are listed in Supplemental Table S4, S5, S6, and S7 for the 2017 experiment, 2018 experiment one, 2018

Table 2. Comparison of physiological and chemical traits between soilless and soil-based cultivations.

Trait	Soilless	Soil	Increase%**	Experiment
Number of fruit on base cluster	4.1a ± 0.18*	2.3b ± 0.14*	79.1**	2017
Height (cm)	69.3a ± 1.66	62.8b ± 1.39	10.3	
Stem diameter (mm)	11.5a ± 0.51	9.9b ± 0.50	15.8	
Vitamin C (mg/100g)	28.0a ± 0.68	24.5b ± 0.84	14.4	2018 one
Soluble solids (%)	7.1a ± 0.18	6.5b ± 0.12	9.2	
Total soluble sugar content (mg/g)	51.0a ± 1.58	43.2b ± 1.01	18.0	
Nitrate content (mg/kg)	97.0b ± 5.19	118.2a ± 2.93	−17.9	
Number of fruit cluster	7.9a ± 1.86	6.4b ± 2.26	23.1	2018 two
Fruit yield (kg/667m^2)	5,202.2a ± 494.95	4163.8b ± 312.27	24.9	
Number of fruits per cluster	20.1a ± 0.15	19.1b ± 0.12	5.2	
Single fruit weight (g)	15.7a ± 0.51	14.3b ± 0.74	9.9	
Fruit cracking rate (%)	0.7b ± 0.22	5.4a ± 1.29	−87.8	
Vitamin C (mg/100g)	19.4a ± 0.56	15.9b ± 1.19	22.3	2019
Soluble solids (%)	6.1a ± 0.16	5.7b ± 0.12	6.3	
Total soluble sugar content (mg/g)	41.1a ± 1.78	35.6b ± 0.25	15.5	
Fruit yield (kg/667m^2)	6,370.4a ± 157.65	5,816.2b ± 187.86	9.5	
Nitrate content (mg/kg)	357.3b ± 14.59	644.5a ± 63.00	−44.6	

* Significant at $P = 0.05$ level in raw, the value signifies the least squared mean for each trait in the two treatments and standardize error.
** Increase% = percentage increasing for soilless compared to soil cultivation = 100 × (soilless soil)/soil), such as for 'Number fruit first era' = 100 × (4.1 − 2.3)/2.3 = 79.1%

Table 3. Comparison of plant growth, fruit yield and fruit qualities between soilless and soil-based cultivations by each tomato cultivar, respectively.

Cultivar	Cultivation	Number of fruits on base cluster		Height (cm)		Stem diameter (mm)		Experiment
		LSM	Increase%	LSM*	Incease% **	LSM	Increase%	
Fenyuan	Soilless	4.1a	141.2	62.3a	8.9	12.65a	24.8	2017
	Soil	1.7b		57.2b		10.14a		
Xiariyangguang	Soilless	4.2a	82.6	76.1a	13.2	13.96a	34.2	
	Soil	2.3b		67.2b		10.40b		
Hongyu	Soilless	5.3a	82.8	69.1a	6.1	14.36a	28.8	
	Soil	2.9b		65.1b		11.15b		
Yuanwei NO.1	Soilless	4.4a	83.3	79.1a	15.8	9.96a	18.1	
	Soil	2.4b		68.3b		8.43a		
Ziyu	Soilless	4.2a	90.9	65.2a	16.2	11.8a	22.9	
	Soil	2.2b		56.1b		9.6a		

Cultivar	Cultivation	Vitamin C (mg/100 g)		Soluble solids (%)		Total soluble sugar content (mg/g)		Nitrate content (mg/kg)		Experiment
		LSM	Increase%	LSM	Increase%	LSM	Increase%	LSM	Increase%	
Fenyuan	Soilless	29.65a	26.7	7.91a	20.8	56.21a	23.2	80.6b	−29.9	2018 one
	Soil	23.41b		6.55b		45.64b		115.0a		
Xiariyangguang	Soilless	30.22a	10.7	7.12a	9.5	54.69a	24.8	108.2b	−9.6	
	Soil	27.31b		6.5a		43.82b		119.7a		
Huangzhenzhu	Soilless	26.12a	14.0	7.09a	12.5	45.69a	13.6	108.2b	−9.6	
	Soil	22.91b		6.3a		40.21b		119.7a		

Cultivar	Cultivation	Number of fruits cluster		Fruit yield (kg/667 m^2)		Fruit weight (g)		Number of fruits per cluster		Fruit cracking rate (%)		Experiment
		LSM	Increase%	LSM	Increase%	LSM	Increase%	LSM	Increase%	LSM	Increase%	
Fenyuan	Soilless	8.2a	20.6	87,003.9a	10.8	16.1a	0.6	21.7a	26.9	0.23b	−92.6	2018 two
	Soil	6.8b		78,541.3b		16.0a		17.1b		3.1a		
Xiariyangguang	Soilless	8.3a	38.3	115,446.4a	50.9	16.8a	52.7	30.2a	−2.3	2.1b	−72.7	
	Soil	6.0b		76,528.4b		11.0b		30.9b		7.7a		
Hongyu	Soilless	8.1a	22.7	56,571.1a	29.2	17.9a	5.3	13.5a	29.8	0	0.0	
	Soil	6.6b		43,787.1b		17.0a		10.4b		0		
Huangzhenzhu	Soilless	8.1a	30.6	55,538.5a	2.6	13.9a	6.9	18.1a	1.1	0.7b	−93.6	
	Soil	6.2b		54,139.5a		13.0a		17.9a		10.9a		

Cultivar	Cultivation	Vitamin C (mg/100g)		Soluble solids (%)		Total soluble sugar content (mg/g)		Fruit yield (kg/667m^2)		Nitrate content (mg/kg)		Experiment
		LSM	Increase%	LSM	Increase%	LSM	Increase%	LSM	Increase%	LSM	Increase%	
Jinpeng 11	Soilless	20.9a	21.5	6.5a	27.5	46.1a	29.9	100,294.5a	2.6	331.58b	−57.8	2019
	Soil	17.2b		5.1b		35.5b		97,797.0a		785.24a		
Fengshouhuang	Soilless	19.6a	39.0	6.0a	7.1	37.9a	6.5	90,274.5a	5.8	394.13b	−21.8	
	Soil	14.1b		5.6b		35.6b		85,342.5b		503.69a		

* LSM = least squared mean.
** Increase% = percentage increasing for soilless cultivation with application of nutrient solution compared to soil-based cultivation with regular irrigation and fertilization as control = 100 × (soilless − soil)/soil, such as for 'Number fruit first era' in the 2017 experiment = 100 × (62.3–57.2)/57.2 = 8.9%

experiment two, and the 2019 experiment, respectively.

In the 2017 experiment, T2 solution showed the highest for all three traits, height, number of fruits on base cluster, and stem diameter across five cultivars, except for height in Fenyuan as the second; all five solutions (T1 to T5) had greater values than the control (soil cultivation); the cultivar Yuanwei NO.1 showed the highest for height across the five solutions and the control, but Hongyu was largest for number of fruits on base cluster and stem diameter across the six treatments (Supplemental Table S4), indicating that T2 was the best solution; Yuanwei NO.1 was highest in plant height; and Hongyu had largest number of fruits on the base cluster and stem diameter. Overall, there was no significant difference for the Cultivar × Treatment interaction in the 2017 experiment (Supplemental Table S3).

In 2018 experiment one, T2 solution showed the highest for three beneficial traits, vitamin C, soluble solids, and total soluble sugar content across the three cultivars, not the lowest for nitrate content but no significance with the lowest (Supplemental Table S5). All five solutions (T1 to T5) had greater values than the control (T6) for the three beneficial traits and lower values than the control in non-beneficial trait nitrate content. Fenyuan performed best in the three traits, nitrate content (lowest), soluble solids, and total soluble sugar content among the three cultivars across all six treatments; but Xiariyangguang had the highest value of vitamin C. The results from 2018 experiment two suggested that T2 was the best solution and Fenyuan was a better cultivar. Overall, there was no significant difference for the Cultivar × Treatment interaction in 2018 experiment one (Supplemental Table S3).

In 2018 experiment two, T2 solution showed the highest for four beneficial traits, fruit yield, single fruit weight, number of fruits per cluster, and number of fruit clusters across the four cultivars except for single fruit weight in Hongyu as second but there was no significant difference among the five treatments; T2 did not showed the lowest for the non-beneficial trait fruit cracking rate in the four cultivars, but there were no significant differences among the five treatments (solutions) (Supplemental Table S6). Xiariyangguang showed the best for number of fruit clusters and single fruit weight; Fenyuan had the lowest fruit cracking rate; and Hongyu was the best for fruit yield across the five treatments (solutions); but for number of fruits per cluster, Hongyu showed the highest in solutions T1 and T5, and Fenyuan was the highest in T2, T3, T4, and T6, indicating that there was interaction between cultivar and treatment (solution).

In the 2019 experiment, T2 solution showed the highest for four beneficial traits, vitamin C, fruit yield, soluble solids, and total soluble sugar content in the two cultivars with the exception of nitrate content but there was no significant difference among five treatments; Fengshouhuang had lower nitrate content and higher soluble solids than Jinoeng; but Jinpeng was higher in total soluble sugar content, vitamin C, and fruit yield (Supplemental Table S7), indicating that T2 was the best solution and there was interaction between cultivar and treatment.

DISCUSSION

The parameters of plant growth, fruit yield and fruit qualities under soilless cultivation

We measured a total of 12 traits in four experiments over three years, including number of fruits on the base cluster, height, stem diameter, vitamin C, soluble solids, total soluble sugar, nitrate content, fruit yield, single fruit weight, number of fruits per cluster, number of fruit clusters, and fruit cracking (Supplemental Table S1)[14,15]. Nitrate is a harmful chemical in foods and is considered a negative trait, as it can form a strong carcinogen-nitrosamine, which may lead to the digestive system's carcinogenesis[16,17]. The purpose of this study was to increase fruit yield and improve plant growth and fruit quality with increasing fruit nutritional components, meanwhile decreasing the toxin level of nitrates in tomatoes. According to the results from this study, soilless cultivation supplied nutrient solutions surpassed soil-based cultivation in all-tested plant growth and fruit yield related traits: number of fruits on the base cluster, height, stem diameter, fruit yield, single fruit weight, number of fruits per cluster, and number of fruit clusters; improved nutritional components: vitamin C, soluble solids, and total soluble sugar content; reduced nitrate content; and decreased the bad fruit trait - fruit cracking (Tables 1 & 2, Supplemental Figs S1−S4), which were consistent with previous reports[6,12,15]. While considering the limitations of space in the greenhouse, cost in chemical analysis and in labor, and the availability of tomato seeds, we did not use all eight-tomato cultivars in the four experiments and did not observe all 12 traits in each of the four experiments. We did find that all 12 traits showed advantage in soilless cultivation over soil-based cultivation and similar results were observed across four experiments. For the three beneficial nutritional components, vitamin C, soluble solids, and total soluble sugar content, these were observed to have higher values in soilless cultivation than soil-based in both experiments in 2018 and in 2019 (Table 2), meanwhile soilless cultivation decreased nitrates in both experiments. The same situations were observed for fruit yield which increased in both experiments in 2018 and 2019; and number of fruits per cluster in both experiments in 2017 and in 2018 (Table 2). We also noticed some related traits that may partially reflect other un-detected traits from different experiments. For example, in 2017, we did not have any data for fruit yield, but the number of fruits per cluster was observed in 2018 and it was an important trait to reflect the total yield. However, we collected the parameters for both traits in 2018 and found that there was a high correlation ($r = 0.86$) between number of fruits per cluster and fruit yield (Supplemental Table S2). We also found that the total soluble sugar content and fruit yield were highly correlated ($r = 0.83$) (Supplemental Table S2)[18]. However, such relationships cannot be arbitrarily extrapolated to the real data, but in some cases, especially in a labor shortage and greenhouse space limitation, this approach without uniformed experiments can be regarded as an acceptable alternative.

Influence of nutrient solutions on the performance of tomatoes

We applied five nutrient solution formulas with two concentrations to different growth stages of the tomatoes. The

Table 4. Five treatments with different nutrient solutions for soilless cultivation and one control of soil-based cultivation.

Treatment	Nutrient solution	Components of each nutrient solution (mg/L)[a]										pH	EC (mS/cm)
		$Ca(N0_3)2\cdot 4H_2O$	KH_2PO_4	KNO_3	$MgSO_4\cdot 7H_2O$	Fe-EDTA	H_3BO_3	$ZnSO_4\cdot 7H_2O$	$MnSO_4\cdot 4H_2O$	$CuSO_4\cdot 5H_2O$	$(NH_4)2MoO_4$		
T1	Formula-1[b]	850	150	430	510	20	3	1.9	1.9	0.07	0.1	5.5–6.8	1.5–2.5
	Formula-2[b]	850	200	430	510	25	3	2	1.9	0.07	0.1	6.5–6.8	2.5–3.5
T2	Formula-1	860	155	440	520	25	4	2	2	0.08	0.12	5.5–6.8	1.5–2.5
	Formula-2	860	210	440	520	28	4	2.1	2	0.08	0.12	6.5–6.8	2.5–3.5
T3	Formula-1	855	153	435	515	23	3.5	1.95	1.95	0.075	0.11	5.5–6.8	1.5–2.5
	Formula-2	855	205	435	515	27	3.5	2.05	1.95	0.075	0.11	6.5–6.8	2.5–3.5
T4	Formula-1	858	154	438	518	24	3.8	1.98	1.98	0.078	0.118	5.5–6.8	1.5–2.5
	Formula-2	858	208	438	518	27	3.8	2.08	1.98	0.078	0.118	6.5–6.8	2.5–3.5
T5	Formula-1	852	151	432	512	21	3.1	1.92	1.92	0.073	0.105	5.5–6.8	1.5–2.5
	Formula-2	852	202	432	512	26	3.2	2.02	1.92	0.072	0.105	6.5–6.8	2.5–3.5
T6	Formula-1 Formula-2	The soil-based cultivation was applied with regular irrigation and fertilization as control; balanced water-soluble fertilizer (N:P:K = 20:20:20) was used in the early fruit setting period, and high-potassium water-soluble fertilizer (N:P:K = 15:5:30) was used in the full fruit setting period.											

[a] H_2O was dded to make 1000 ml for each solution of either Formula-1 or Formula-2 from T1 to T5.
[b] Formula-1 was supplied in seedling and budding stages and Formula-2 in early fruiting and ripening stages.

challenge in this part includes what kinds of solution and when we should supply nutrient solution to tomato soilless cultivation, and how to balance the conflict between fruit yield and quality while taking into account the differences between tomato cultivars [19]. Our previous experiments found that it was most reasonable to divide the nutrition supply into four phases: seeding, budding, early fruiting, and fruit-ripening stages. The nutrient supply at seedling and budding was aiming to promote the development of roots and stems for the first two stages. Although root and stem development had little effect on the number of flowers, it has a critical impact on budding time, fruit number, and fruit development [20,21]. Based on previous studies, a fixed time to switch the nutrient formula or concentrations to soilless cultivation at early fruiting will promote the plants fruiting on time, when the nutrient formula-1 was supplied (Table 4). In contrast, nutrient formula-2 was applied strictly according to plant development (fruiting stage and ripening stage) rather than growth stage, as the nutrient formula-2 was not applied to the plants until the first fruit appeared[22].

All five treatments from T1 to T5 had significantly higher values than the control (T6) compared to the soil-based cultivation for tomato plant growth, fruit yield and quality. Each treatment increased plant growth and fruit yield related traits: number of fruit on the base cluster, height, stem diameter, fruit yield, single fruit weight, number of fruits per cluster, and number of fruit cluster; improved nutritional components: vitamin C, soluble solids, and total soluble sugar content; reduced nitrate content; and decreased the bad fruit trait fruit cracking rate (Tables 1 & 2, Supplemental Figs S1–S4). According to the results, the treatment-2 (T2) (Table 4) was the best solution: increasing 91.3% for number of fruit on the base cluster, 12.1% for height, and 26.3% for stem diameter in the 2017 experiment; 17.1% for vitamin C, 13.8% for soluble solids, and 20.8% for total soluble sugar content in 2018 experiment one; 28.1% for number of fruit cluster, 25.8% for fruit yield, 9.4% for number of fruit per cluster, and 13.3% for single fruit weight in 2018 experiment two; and 27.7% for vitamin C, 14.0% for soluble solids, 18.1% for total soluble sugar content, and 14.6% for fruit yield in the 2019 experiment. The T2-solution decreased nitrate content by 16.2% in the 2018 experiment and 43.7% in the 2019 experiment, and also decreased the fruit cracking rate by 87% (Tables 1 & 2, Supplemental Tables S4–S7, Supplemental Figs S1–S4).

The soilless technology in this study

Soilless cultivation can be defined as: 'Any method instead of using soil as a rooting medium for plant growth, where the inorganic nutrients absorbed by the roots are provided through irrigation water[7]. The advantages of the system are no soil-borne pathogens; safe methods of soil disinfection; and nutrients and water are more evenly applied to plants, thus reducing waste and providing an environment close to ideal growing conditions. In recent decades, it has become routine practice to provide plants with nutrient solutions to optimize crop nutrition (fertilization or liquid fertilization)[23]. According to the plants different growth stages, our study carried on multi-formula nutrition solutions with its advanced production strategy[4]. It is also worth noting that the experimental data were collected from large-scale real greenhouse farms in tomato production. Since this study's design was based on decades of experience and records that were accumulated in actual large-scale production, it was hard to address a single factor explanation in terms of formula design and delivery time. Despite the flaw on considering the relatively high equipment management and labor cost of soilless cultivation, our study is a rare and valuable reference.

Tomato is one of the main vegetable crops worldwide. The growth of tomato is complex and is affected by multiple factors such as crop systems, substrates, and water supply. Traditional soil cultivation can regulate tomatoes through irrigation, but it will cause continuous cropping obstacles. Water regulation is difficult to control, thus leading to over supply of water and fertilizer and lowers yield and quality. Nevertheless, soilless cultivation is more conducive to precise supply of water and fertilizer. Inorganic substrate nutrient solution cultivation has the advantages of balanced supply of nutrient elements, easy control, and protection of crops from soil-borne diseases. The use of a closed cultivation environments and nutrient solution circulation systems has the potential to improve water and fertilizer use efficiency, reduce soil-borne diseases, and increase crop yield and quality. Our study is consistent with the results reported by Li et al.[24]. In our study, we used the renewable resource perlite as the substrate, tomato cultivars were grown under a specially designed cultivation tank, supplied nutritional fertilizer and irrigation water. The recycling of nutrient solution resulted in tomato with both high-yield and high quality. The system used perlite with good water permeability and air permeability, which solved the problem of salt accumulation or rotting roots caused by too little or too much irrigation in traditional organic substrates such as grass charcoal and coconut bran in production. Shi et al.[25] used the tank system for tomato soilless cultivation and reported that this system ensured the yield and quality of tomatoes and the water-saving effect was significant. The intermittent liquid supply can increase tomato fruit yield, improve fruit quality, and increase water and fertilizer use efficiency more than continuous liquid supply[26−28], and thus improve the quality of the fruit, and the liquid supply in an intermittent manner that promotes plant growth more than continuous liquid supply.

CONCLUSIONS

Twelve traits of tomato were evaluated under inorganic substrate soilless cultivation in this study. The soilless cultivation supplied with nutrient solutions surpassed soil-based cultivation in all-tested plant growth and fruit yield related traits: number of fruit on the base cluster, height, stem diameter, fruit yield, single fruit weight, number of fruits per cluster, and number of fruit clusters; improved nutritional components: vitamin C, soluble solids, and total soluble sugar content; reduced nitrate content; and decreased the fruit cracking rate. Treatment 2 with higher mineral nutrient content performed the best among the five treatments. This study showed that soilless cultivation could bring advantages over soil-based cultivation in tomato production.

MATERIALS AND METHODS

Plant materials

Six-cherry tomato cultivars, 'Yuanwei NO.1', 'Fenyuan', 'Ziyu', 'Hongyu', 'Xiariyangguang', and 'Huangzhenzhu', and two big fruited tomato cultivars, 'Jinpeng 11' and 'Fengshouhuang' were used in this study (Supplemental Table S8).

Experimental design and soilless nutrient solutions

Four experiments were conducted under substrate soilless cultivation in the controlled-environment greenhouses at the High-tech Vegetable Science and Technology Park of Hebei Province, and the Physiology and Biochemistry Laboratory of the Economic Crops Research Institute of Hebei Academy of Agricultural and Forestry Sciences, Shijiazhuang, China from 2017 to 2019. Because each experiment was conducted in a large-scale study in greenhouse production conditions, it was difficult to implement our experiments for tomatoes under real production conditions. Due to the limitation of our greenhouse space and the availability of tomato seeds, we conducted four separate experiments with different tomato cultivars and measured different physiological and chemical traits of the plant growth, fruit yield and fruit quality. Five tomato cultivars, Yuanwei NO.1, Fenyuan, Ziyu, Hongyu, and Xiariyangguang were used in the 2017 experiment; three cultivars, Fenyuan, Xiariyangguang, and Huangzhenzhu in 2018 experiment one; four cultivars, Fenyuan, Hongyu, Xiariyangguang, and Huangzhenzhu in 2018 experiment two; and two cultivars, Jinpeng 11 and Fengshouhuang in the 2019 experiment. The number of fruits on base cluster, height, and stem diameter were measured in the 2017 experiment; vitamin C, soluble solids, total soluble sugar content, and nitrate content were measured in 2018 experiment one; number of fruit clusters, fruit yield, number of fruits per cluster, single fruit weight, and fruit cracking rate were measured in 2018 experiment two; and vitamin C, soluble solids, total soluble sugar content, fruit yield, and nitrate content were measured in the 2019 experiment.

In each experiment, a closed inorganic substrate cultivation technology was used under soilless inorganic substrate conditions. The perlite was used as a soilless culture substrate, and it was an inert, sterile substrate, with good stability, good water retention and air permeability, but does not interfere with the nutrient solution and can't be absorbed or utilized by plants[29]. Before being planted in soilless inorganic substrate, the seeds for each tomato cultivar were germinated in 72-cell (hole) plastic trays at one seed per cell, which contained waste mushroom material cottonseed skin: vermiculite at 2:1 (v/v). After 25 d, the uniform seedlings were selected and transplanted to the soilless cultivation tank system with 50 cm width and 30 cm height and the length as the same length as the greenhouse, accordingly.

The experimental design was a randomized complete block design (RCBD) with three replicates organized in a split-plot manner, where the nutrient solution as the main plot and the tomato cultivar as the sub-plot. There were six treatments: T1, T2, T3, T4, T5, and T6 (control) in this study (Table 4). The five treatments from T1 to T5 were inorganic substrate nutrient solutions used in soilless cultivation, and each treatment includes two nutrient solution formulas, used in the early stage and the fruit setting period, respectively. The nutrient elements of the five treatments are the same, but the difference lies in the different concentrations of the macronutrients.

The soil-based cultivation of treatment 6 (T6) was applied with regular irrigation and fertilization as control. A balanced water-soluble fertilizer (N:P:K = 20:20:20) was used in the early fruit setting period, and high-potassium water-soluble fertilizer (N:P:K = 15:5:30) was used in the full fruit setting period.

In each treatment, 50 plants of each tomato cultivar were transplanted and grown in a single row of the tank system as one experiment block. Therefore, a total of 900 plants per cultivar were transplanted and grown in each experiment (Fig. 1).

Four doses of nutrient solution were applied in four tomato growth stages: seedling (10 d after transplanting), budding (40 d after transplanting), and early fruiting (first ear fruit set), and fruiting-ripening (from first ear fruit set to fruit harvesting) for each of the six treatments. In each treatment, two different formulas of nutrient solutions were supplied: one called 'Formula-1' at seedling and budding, and another defined as 'Formula-2' at early fruiting and fruiting-ripening (Supplemental Table S4). Therefore, there was a total of 10 different formulas of nutrient solutions plus one control of soil-based cultivation in this study. The control was the soil-based cultivation with regular irrigation and fertilization listed as 'T6 = Treatment 6' in this study.

The nutrient solutions were pumped into the soilless system for 10, 15, 20, and 22 mins every 2 h in the four stages, respectively. The potential of hydrogen (pH) and electrical conductivity (EC) were adjusted to different values at the four stages: pH 5.5−6.8 and EC 1.5−2.5 mS/cm at seedling and budding, and pH 6.5−6.8 and EC 2.5−3.5 mS/cm at early fruiting and fruit ripening (Table 4).

Phenotyping for plant growth, fruit yield and quality

We randomly selected 15 out of the 50 plants in each treatment for phenotyping. Eight physiological traits as plant growth and fruit yield related, plant height, stem diameter, number of fruit clusters, number of fruits on the base cluster, number of fruits per cluster, single fruit weight, fruit yield and fruit cracking rate were observed and measured before harvesting with the exception of single fruit weight and fruit

Fig. 1 Tomato soilless cultivation (left) and soil-based cultivation (right) in the greenhouse: (a) inorganic soilless substrate cultivation at seedling stage, (b) soil-based cultivation at seedling stage, (c) inorganic soilless substrate cultivation at fruiting stage, and (d) soil-based cultivation at fruiting stage in tomato cultivar 'Fenyuan'.

yield, which were measured after harvesting. Four chemical contents as the fruit quality, nitrate content, soluble solids, total soluble sugar content, and vitamin C were analyzed from the selected 15 plants in each treatment with three replicates. Nitrate (NO_3^-)[30] and the soluble sugar contents[31] were determined using a spectrophotometer (SP-1900 ultraviolet; Spectrum, Shanghai, China); soluble solid content was determined using a sugar meter (PAL-1; Atago, Shenzhen, China)[32]; and vitamin C was determined by 2,6-dichlorophenol indophenol titration[33]. All the monitoring and controlling of environmental conditions, including temperature, humidity, light, oxygen, and pH, were recorded automatically by a computer system (Siemens Smart Line, Hebei Agricultural Mechanization Research Institute Co. LTD. Hebei Province, China).

Statistical analysis

The phenotypic data in each of the four experiments were analyzed using the analysis of variance (ANOVA) with the general linear models (GLM) procedure of JMP Genomics 7 (SAS Institute, Cary, NC, USA). The *t* test at α = 0.05 was used for multiple comparisons of the least square mean among the treatments and among tomato cultivars. The mean, minimum value (min), maximum value (max), range, variance, standard deviation (SD), standard error (SE), and coefficient of variation (CV) were estimated for each trait using 'Tabulate'. Pearson's correlation coefficients (r) were calculated using 'Multivariate Methods'. The distributions were drawn using 'Distribution' in JMP Genomics 7 or using Microsoft Excel 2016.

Conflict of interest

The authors declare that they have no conflict of interest.

Supplementary Information accompanies this paper at (https://www.maxapress.com/article/doi/10.48130/TIH-2022-0005)

Dates

Received 22 March 2022; Accepted 30 June 2022; Published online 19 August 2022

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