Adjusting the nutrient solution formula based on growth stages to promote the yield and quality of strawberry in greenhouse

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Abstract: To optimize the nutrient supply of strawberry, fertilization was reduced as much as possible on the premise of satisfying the elements needed for strawberry growth. This study put forward a modified nutrient solution formula (NM) by adjusting the ratios of N/K, K/Ca, NO_3^--N/NH_4^+-N in vegetative growth, flowering and fruiting, and fruit expanding stages based on Yamasaki strawberry nutrient solution formula (NY). Taking the NY as the control group, the NM was verified with elevated-grown ‘Ssanta’ strawberry using three different substrates (Vulcanics-added substrate, Horticultural substrate, Comme rcial substrate) in greenhouse. The results indicated that under the NM treatment, strawberry plants had better photosynthesis in the vegetative growth stage and flowering and fruiting stage, and the first crop yield and total crops yield per plant also increased by 20%. Although the vegetative growth stage was longer, it entered the full fruiting stage earlier so that the maturity stage was advanced one week. Compared to strawberries grown in horticultural substrate irrigated with NY, the fruit yield per plant of ‘Ssanta’ strawberry grown in horticultural substrate irrigated with NM increased by 26%, and the sugar-acid ratio and vitamin C content of primary fruits reached 10.6 and 74.1 mg/100g, improving by 41% and 34% respectively. The NM based on the growth stage can optimize the element needs of strawberry in all growth and development stages and maintain the substrate’s pH stability, improving the yield and quality of ‘Ssanta’ strawberry under substrate cultivation. Therefore, it is recommended to use the horticultural substrate irrigated with the modified nutrient solution for the ‘Ssanta’ strawberries cultivation elevated in greenhouse to improve the economic benefit of strawberry cultivation.

Keywords: elevated-grown strawberry, nutrient solution formula, substrate cultivation, phenological stage, fruit yield, fruit quality

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1 Introduction

Strawberry (*Fragaria×ananassa* Duch) is a perennial herbaceous plant of the strawberry genus in Rosaceae. It is widely cultivated because of its short planting period and high economic benefit[1]. In 2020, the total planting area and annual yield of strawberry in China were 1.27×10^5 hm^2 and 3.34×10^6 t, respectively, accounting for 33.1% and 37.7% of the total planting area and annual yield of strawberry in the world, which ranked first in the world[2]. Despite the large scale of strawberry production in China, the yield per unit area was only 2.4-2.8 kg/m^2, which was still far from that of the United States, the Netherlands, and Japan. The low yield per unit area and continuous cropping obstacles[3-5] are the main constraints to the sustainable development of the strawberry industry in China.

Traditional soil cultivation had problems such as continuous cropping obstacles, soil exhaustion, and soil-borne diseases[6,7], and substrate cultivation of facility strawberries is conducive to solving these problems[8]. Substrate cultivation is a mainstream cultivation mode for soilless cultivation of plants, which usually provides inorganic nutrients to strawberry plants through nutrient solution[9], this cultivation mode could improve water and nutrient utilization efficiency and increase yield and profits[10,11]. The substrate cultivation of strawberries usually uses a single nutrient solution formula during the whole growth stage with EC/pH adjustment for different substrates, currently[12]. However, for fruit-bearing crops, the relative need for nutrients is not constant throughout the crop, but there is a shift in the ratio between the different nutrients[13]. In addition, Fattahi et al.[14] found that the nutrient conditions required by strawberry plants at different growth stages differ greatly. The ion concentrations of nitrogen, phosphorus, and potassium in the nutrient solution with a reasonable ratio could improve the content of vitamin C, soluble sugar, and so on effectively in strawberry fruits[15,16], and strawberry yield and quality could be improved by optimizing nutritional conditions[17,18]. Therefore, it is necessary to have fine management of the ionic composition of strawberry nutrient solution.

Of the essential nutrients for strawberry cultivation, N stands out as one of the most important for promoting vigorous plant growth[19]; K plays a role in enzymatic activation, protein synthesis and photosynthesis[20]; Ca is an important factor for cell wall and membrane stability[21]. The relationship between N and K determines

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the balance between vegetative growth, fruit quality, and reproductive processes[22]. The K/Ca ratio has an effective role in mineral uptake, growth, and product quality[23]. In addition, adjusting the NO_3^--N/NH_4^+-N could be the main tool to maintain pH within the desired range[24]. The ratio of N/K, K/Ca, and NO_3^--N/NH_4^+-N in Yamazaki strawberry nutrient solution were 1.8, 1.5, and 10, respectively[25]. In the N-K interaction, an N/K ratio of 1.7 maximized the yield, antioxidant capacity, and phenolic compounds of strawberry[22]. Plants need different nutrients ratio basis on the growth stage, thus need to determine the best ratio of K/Ca according to the growth stage[26]. During the vegetative growth stage, strawberry plants have a high demand for potassium, which helps activate photosynthesis and regulates protein synthesis, sugar and water balance of strawberry plants[27]. K/Ca ratios between 1 to 1.6 did show a favorable effect on strawberry yield and quality, furthermore, 1.4 was the more efficient K/Ca ratio for high quality strawberry 'Selva' production. In addition, strawberry plants grow vigorously during the vegetative growth stage and absorb a large amount of nitrogen, which could cause the pH of the substrate to rise easily, and increasing NH_4^+ content is beneficial in preventing pH rise. Strawberry plants need more cations during the flowering and fruiting stage, and increasing potassium content is helpful to fruit development, but the pH of the substrate is easy to decrease when the potassium increase, thus reducing NH_4^+ content at this time could prevent pH from falling too fast. At the fruit expanding stage, strawberry plants absorb a large amount of potassium and transport it from leaves to fruits, which is conducive to improving fruit yield and quality[28].

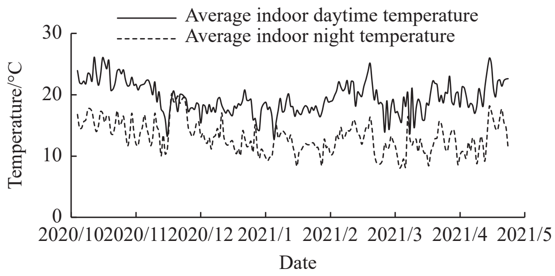
An increasing number of studies have shown that strawberry plants have different requirements for nutrient elements at the different development stages, thus, using the same nutrient solution throughout the whole growth stages is not conducive to the achievement of the high-quality and efficient yield. Strawberry has higher requirements for nitrogen and calcium at the vegetative growth stage, and higher requirements for potassium at the flowering and fruiting stage and fruit expanding stage, meanwhile, the property of the substrate also plays a crucial role in determining nutrient and water availability for the strawberry plant[29]. Therefore, this research proposed a modified strawberry nutrient solution formula for strawberry and studied the efficacy of this formula on the yield and quality of elevated-grown 'Ssanta' strawberry under three substrates, in the hope of providing technical support for the quality and efficient yield of elevated-grown strawberry in greenhouse.

2 Materials and methods

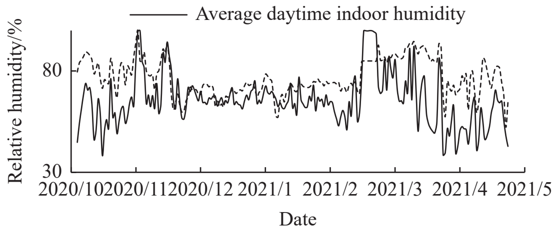
2.1 Plant materials and growing conditions

The experiment was conducted in a multi-span film greenhouse in the east zone of the National Modern Agricultural Science and Technology Demonstration Park, Xiaotangshan, Changping District, Beijing (116°26'E, 44°9'N) from September 15, 2020 to March 22, 2021. The greenhouse is located in the north-south direction, with a shoulder height of 5.2 m, a ridge height of 3.7 m, a bay of 5 m and a span of 8 m, a total of 10 spans and 25 bays, a floor area of 10 000 m^2, and covering material of 0.15 mm high-transport trickle defogging membrane with aeration on roof and sides.

'Ssanta' strawberry is a short-day variety with excellent fruit production and quality. The runner plants with a crown diameter of around 8 mm and five leaves were obtained from a plastic tunnel in Shanxi. The strawberry plants were planted in staggered rows in a type-H groove (30 cm wide and 15 cm deep) for elevated-grown with a plant spacing of 20 cm. The transplants were irrigated after planting immediately and uniformly managed, later covered with a black heat-preserving membrane. The old leaves were cut off every two weeks after the strawberry plants enter the flowering and fruiting stage, leaving 5-6 leaves at the flowering and fruiting stage, 7-8 leaves at the fruiting expanding stage. Bees were released into the greenhouse for pollination at the flowering stage. The temperature and relative humidity inside the greenhouse during strawberry cultivation are shown in Figures 1a and 1b. Horticultural substrate, Japanese strawberry special substrate, and Shandong Shangdao strawberry special substrate are three commonly used strawberry cultivation substrates. The initial physical and chemical properties of the three substrates are shown in Tables 1 and 2.



a. Temperature



b. Relative humidity

Figure 1 Change of temperature and relative humidity inside the multi-span film greenhouse

Table 1 Initial physical properties of strawberry culture substrates

Treatment	Bulk density/g·cm^{-3}	Total porosity/%	Air porosity/%	Water-holding porosity/%	Air-water ratio
SH	0.17±0.01^{b}	73.6±1.3 NS	8.1±0.8^{ab}	65.4±1.7 NS	0.12±0.01^{ab}
SV	0.19±0.01^{b}	75.0±0.6 NS	9.2±1.1^{a}	65.8±0.9 NS	0.14±0.02^{a}
SC	0.23±0.03^{a}	74.3±2.4 NS	6.4±0.5^{b}	67.9±2.8 NS	0.09±0.01^{b}

Table 2 Initial chemical properties of strawberry culture substrates

Treatment	pH	EC/mS·cm^{-1}	The content of alkali-soluble organic matter/%	The content of available phosphorus/ mg·kg^{-1}	The content of rapidly available potassium/ mg·kg^{-1}
SH	5.90±0.40^{b}	0.09±0.00^{c}	0.33±0.05^{b}	11.6±1.7^{c}	260.9±69.2^{b}
SV	6.31±0.14^{a}	0.31±0.04^{b}	0.39±0.06^{b}	58.5±11.1^{b}	178.3±44.1^{c}
SC	6.27±0.02^{a}	1.08±0.43^{a}	1.57±0.14^{a}	122.5±20.1^{a}	957.6±149.7^{a}

2.2 Experimental design

The strawberry cultivation was divided into the vegetative growth stage (from September 15 to October 20), flowering and fruiting stage (from October 20 to November 20), and fruit expanding stage (from November 20 to December 20). The drip irrigation was used in the elevated cultivation of strawberries. The daily nutrient solution amount used in irrigation of application differed by the whole development stages. In the vegetative growth stage, the nutrient solution was irrigated once a day at 9:00 a.m. with 80 mL/d per plant; while irrigated twice at 9:00 a.m. and afternoon at 2:00 p.m. with 120-150 mL/d per plant in other stages.

The experiment was realized using the soilless in the greenhouse, the cultivation substrates used in this study were common mixed horticulture substrate named Substrate-Horticulture (SH) (vermiculite: peat: perlite=1V:1V:1V), Japanese strawberry special substrate named Substrate-Volcanics (SV) (vermiculite: peat: perlite: volcanic stone: carbonized rice husk=8V:8V:4V:4V: 1V), and Shandong Shangdao strawberry special substrate named Substrate-Commerce (SC). Two different nutrient solution treatments were applied during the strawberry growth stage: Yamazaki strawberry formula (NY: Nutrient-Yamazaki) and modified strawberry formula (NM: Nutrient-Modified) (Table 3). The EC of the nutrient solution was controlled at 0.8-1.4 mS/cm and the pH at 5.8-6.5. The NY solution was used in the whole growth and development stages while the NM solution was prepared according to the vegetative growth stage, flowering and fruiting stage, and fruit expanding stage. A total of six experimental areas (NY-SH, NY-SV, NY-SC, NM-SH, NM-SV, and NM-SC) were set up with the NY-SC as a control group and 90 strawberry plants were planted in each experimental area. At three growth and development stages, the N/K ratios of the modified strawberry nutrient solution formula were 2.2, 1.7, and 1.6; the K/Ca ratios were 1, 1.5, and 2.0; the NO_3^--N/NH_4^+-N ratios were 5.5, 13.3, and 8.6.

Table 3 Composition of nutrient solution of elevated-cultivated strawberry in greenhouse

Reagents	Yamazaki strawberry nutrient solution formula (NY)	Modified strawberry nutrient solution formula (NM)		
	Whole growth and development stages/mg·L^{-1}	Vegetative growth stage/mg·L^{-1}	Flowering and fruiting stage/mg·L^{-1}	Fruit expanding stage/mg·L^{-1}
$Ca(NO_3)_2·4H_2O$	236	354	472	472
KNO_3	303	252	534	724
$MgSO_4·7H_2O$	123	123	246	246
KH_2PO_4	0	68	91	113
$(NH_4)_2SO_4$	0	66	46	86
$NH_4H_2PO_4$	57.5	0	0	0
DTPA-Fe^{-7}	28.6			
H_3BO_3	1.13			
$MnSO_4·H_2O$	0.61			
$ZnSO_4·7H_2O$	0.09			
$CuSO_4·5H_2O$	0.04			
$(NH_4)_6Mo_7O_{24}·4H_2O$	0.01			
Proportion of main nutrient elements				
N/K	1.8	2.2	1.7	1.6
K/Ca	1.5	1.0	1.5	2.0
NO_3^--N/NH_4^+-N	10.0	5.5	13.3	8.6

2.3 Measurements

2.3.1 Physical properties of substrate

Substrate physical properties were measured by ring knife method, including substrate bulk density (γ, g/cm^3), total porosity (φ, %), air porosity (φ_a, %), water-holding porosity (φ_w, %) and air-water ratio (d). A ring knife with a known volume (V, cm^3) was used to measure its mass (M_1, g), and fill the substrate. Wrap the ring knife with waterproof tape of known mass (M_2, g), and soak the ring knife completely in water until the air gap is filled with water, measuring its mass (M_3, g). Drain the ring knife upside down until there is no water leakage and weigh its mass (M_4, g). Finally, dry it in oven and weigh its mass (M_5, g). The parameters of γ, φ, φ_a, φ_w and d can be calculated by the Equations (1)-(5), and water density (ρ) is 1 g/cm^3. The initial chemical properties of the substrate are listed in Table 2.

$$\gamma = \frac{M_5 - M_1}{\rho V} \tag{1}$$

$$\varphi = \frac{M_3 - M_5 - M_2}{\rho V} \times 100\% \tag{2}$$

$$\varphi_a = \frac{M_3 + M_4 - M_2}{\rho V} \times 100\% \tag{3}$$

$$\varphi_w = \frac{M_4 - M_5}{\rho V} \times 100\% \tag{4}$$

$$d = \frac{\varphi_a}{\varphi_w} \tag{5}$$

2.3.2 Chemical properties of substrate

The pH and EC of substrates were measured using a portable multi-parameter water quality analyzer (HQ-40d, HACH Company, USA). The content of alkali-soluble organic matter was measured using an ultraviolet-visible spectrophotometer (UV1700PC, Shanghai Aucy Scientific Instrument Co., Ltd., China) at 680 nm.

2.3.3 Plant morphology and leaf chlorophyll content

Eight plants with uniform and consistent growth were randomly labeled in each treatment at the beginning of different growth stages, and the morphological characteristics of strawberries including crown diameter, petiole length, and leaf number were determined. The crown diameter was measured using a digital vernier caliper, mm; the petiole length of the 3rd fully expanded trifoliate leaf from the inside out was measured by a straight ruler, cm; the strawberry leaf number was determined based on the number of fully expanded mature leaves.

A portable chlorophyll meter (SPAD-502, Konica Minolta Company, Japan) was used to measure the SPAD value, which could represent the chlorophyll content of strawberry leaves. The measurement for leaf samples should avoid the veins, measure five times in each leaf and take the average value.

2.3.4 Photosynthetic characteristics

A portable photosynthesis system (LI-6400XT, LI-COR Inc., USA) was used to measure the photosynthetic parameters including net photosynthetic rate (μmol/m^2·s), stomatal conductance (mmol/m^2·s), intercellular CO_2 concentration (μmol/mol) and transpiration rate (mmol/m^2·s). The standard red and blue light leaf chamber (2 cm×3 cm) was chosen in this study, the light intensity, temperature of blade chamber, CO_2 concentration, and airflow rate in the sample room were set to 400 μmol/m·s, 20°C, 400 μmol/mol, and 500 μmol/s. The third fully-expanded leave of strawberry was selected for photosynthetic characteristics measurement.

2.3.5 Phenological stage

50 plants with consistent growth were selected from each treatment and the strawberry phenological stage, including initial budding stage, full budding stage, initial blooming stage, full blooming stage, initial fruiting stage, and full fruiting stage, were recorded from October 5, 2020 to December 15, 2021. The budding rate, flowering rate, and fruit ripening rate were determined. The

early budding/flowering stage referred to the appearance of buds/flowers in over 25%, whole budding/flowering stage referred to the appearance of buds/flowers in over 75% of the plants in the treatment. The early fruiting stage referred to fruit ripening in over 25%, and the whole fruiting stage referred to fruit ripening in over 75% of plants.

2.3.6 Strawberry yield and quality

Strawberries were harvested three times, from November 18 to December 4, 2020, on January 19, 2021, and from March 11 to March 22, 2021. Six ripe fruits were randomly selected from each treatment to determine fruit weight, firmness, soluble solid content, vitamin C content, total acid content, and soluble sugar content of the first crop strawberry.

A percentile electronic balance was used to measure single fruit weight after ripening and the total yield of strawberry fruits per plant was calculated with a single fruit weight greater than 10 g. Firmness was measured by a penetrometer, and 3 symmetric positions were taken for each fruit, and the results were averaged. Soluble solid content was measured using a digital pocket refractometer (PAl-1, Atago Company, Japan). The soluble sugar content was measured by anthrone colorimetry[30], and the total acid content was measured by acid-base titration[30]. Acid-sugar ratio was calculated after sampling and measuring the soluble sugar content and total acid content. The acidic solution of vitamin C was titrated with basic 2,6-dichlorindo-phenol standard solution with light red as the titration endpoint, and the content of vitamin C in samples was calculated from the amount of 2,6-dichlorindo-indophenol[30].

2.4 Statistical analysis

The data analysis was performed using Microsoft Excel 2019. The statistical analysis of the data was performed using SPSS statistics 26. The analysis of variance was performed using Duncan's new multiple range test at the significance level of α=0.05.

3 Results

3.1 Substrate chemical properties

The pH of the substrates in each treatment showed a decreasing trend, basically within the range of 6.1-6.8 (Figure 2a). The range of NM-SH substrate pH showed at the least degree, which was within 0.05 during cultivation. The EC values of NM and NY treatments varied significantly, but the variation trend was similar, showing a decreasing trend from the vegetative growth stage to the flowering and fruiting stage, and were more stable after the flowering and fruiting stage. Except for NY-SV, which had an EC value of 1.67 mS/cm at the strawberry vegetative growth stage, the EC values of substrates in the other treatments were all in the range of 0.4-1.2 mS/cm.

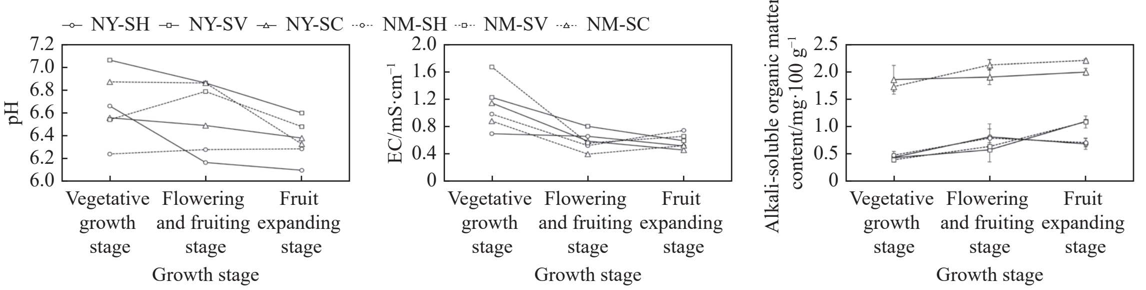


Figure 2 Effects of different nutrient solutions on chemical properties of strawberry culture substrate

There was no significant difference in the content of alkali-soluble organic matter in the substrate between strawberry growth and development stages with different nutrient solution, but the different substrates could affect it significantly (Figure 2c). The alkali-soluble organic matter contents of SC treatments were significantly higher than those of other substrate treatments, ranging between 1.7% and 2.2%, while those of SV treatments and SH treatments were 0.4%-1.1%, and there was no significant difference between SV and SH treatments.

3.2 Morphology of strawberry plants

Adjustment of nutrient solution formula at growth and development stages did not affect stem diameter of strawberry plants but affected plant height and leaf number significantly (Figures 3a-3c). The stem diameter of strawberry plants increased rapidly in the vegetative growth stage, and then slightly decreased after entering the flowering and fruiting stage, basically stabilized at 14-16 mm in the late cultivation stage. This may be because after strawberry plants enter the flowering and fruiting stage, they switch from vegetative growth to reproductive growth, and the absorbed nutrients supply to flowering and fruiting. Compared with NY treatments, the plants' growth of NM treated was less affected by reproductive growth. The strawberry plants in the NY-SC treatment grew better in vegetative growth, the plant height reached 20 cm at the flowering and fruiting stage, which was significantly higher than other treatments which were about 17 cm. The leaf number of strawberry plants increased gradually as plants grew. At the

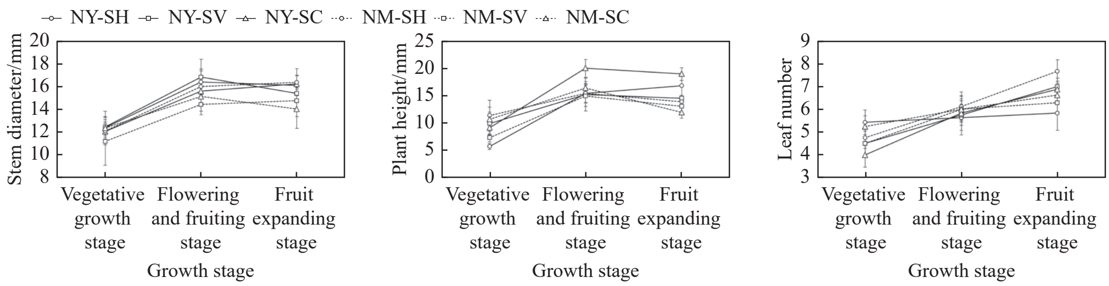


Figure 3 Effect of nutrient solution formula adjustment on the morphology of strawberry

vegetative growth stage, the leaf number of plants in NY treatments was more than that in NM treatments, then slowed down after entering the flowering and fruiting stage. The leaf number of plants in NM-SH treatment was 8 per plant at the fruit expanding stage, significantly higher than other treatments below 7 per plant.

3.3 Photosynthetic characteristics and chlorophyll content

At the vegetative growth stage, the stomatal conductance of strawberry leaves in NM treatments was about 400 mmol/m^2·s, and the transpiration rate was above 8 mmol/m^2·s, respectively, which were significantly higher than in NY treatments, while the differences in net photosynthetic rate and intercellular CO_2 concentration were not significant. At the flowering and fruiting stage, the net photosynthetic rate, stomatal conductance, and intercellular CO_2 concentration of strawberry leaves in NM treatments were significantly higher than those in NY treatments, on the contrary. Adjusting the nutrient solution formula had no significant effect on the net photosynthetic rate, transpiration rate, and intercellular CO_2 concentration of strawberry leaves at the fruit expanding stage (Table 4). The SPAD values of strawberry leaves showed an upward trend as plants grew (Table 4), and were significantly higher in NM treatments than in NY treatments. At the fruit expanding stage, the maximum SPAD value in NM-SH treatment reached 51.6.

3.4 Phenological stage

The adjustment of nutrient solution formula at growth and development stages had a significant effect on the phenological stage of strawberries (Figure 4). Compared with NY treatments, the vegetative growth stage of strawberries in NM treatments was longer, while their flowering and initial fruiting stages were relatively short, and the full fruiting stage was advanced by 7-9 d. Strawberry plants entered the reproductive growth later but entered the full fruiting stage earlier.

Table 4 Effect of nutrient solution formula adjustment on photosynthetic characteristics and SPAD values of strawberry

Treatment	Growth and development stage	Net photosynthetic rate/μmol·m^{-2}·s^{-1}	Stomatal conductance/mmol·m^{-2}·s^{-1}	Transpiration rate/mmol·m^{-2}·s^{-1}	Intercellular CO_2 concentration/μmol·mol^{-1}	SPAD values
NY-SH	Vegetative growth stage	15.4±1.0^a	286±18^c	2.90±0.19^d	294±9^c	46.3±3.2^b
NY-SV		13.8±0.4^b	301±23^c	3.15±0.21^d	308±6^b	44.9±3.1^b
NY-SC		14.8±1.5^{ab}	413±70^{ab}	6.37±1.24^c	319±9^a	45.2±0.8^b
NM-SH		15.0±1.4^{ab}	418±49^{ab}	8.82±0.79^a	315±7^{ab}	46.7±1.7^{ab}
NM-SV		14.1±1.0^{ab}	382±12^b	8.14±0.23^b	315±6^{ab}	45.3±2.^{2b}
NM-SC		15.3±1.0^a	427±25^a	8.88±0.43^a	316±4^{ab}	49.4±0.3^a
NY-SH	Flowering and fruiting stage	12.4±0.7^{bc}	111±8^c	2.93±0.20^a	191±14^c	47.0±1.4^a
NY-SV		11.7±1.0^c	90±7^c	2.45±0.21^b	162±17^b	46.4±1.3^a
NY-SC		12.0±0.3^{bc}	110±7^c	2.93±0.17^a	196±11^a	44.1±1.^{5b}
NM-SH		12.9±1.3^a	229±15^b	2.15±0.26^b	286±6^{ab}	47.5±1.4^a
NM-SV		12.8±0.5^a	264±25^a	2.42±0.19^b	299±4^{ab}	46.9±1.6^a
NM-SC		12.9±0.3^a	270±36^a	2.44±0.23^b	300±8^{ab}	48.0±0.9^a
NY-SH	Fruit expanding stage	12.2±0.6^{ab}	169±12^{bc}	2.47±0.14^a	254±9^{ab}	50.9±1.5^a
NY-SV		12.5±1.1^{ab}	171±14^b	2.49±0.17^a	253±20^{ab}	49.9±2.1^a
NY-SC		12.0±0.3^b	157±10^c	2.39±0.12^a	248±10^b	48.0±1.4^b
NM-SH		11.7±0.3^b	151±8^d	1.91±0.09^b	249±7^b	51.6±2.2^a
NM-SV		12.1±0.4^{ab}	185±13^a	2.33±0.16^a	267±9^a	51.0±1.2^a
NM-SC		12.8±0.8^a	177±8^{ab}	1.98±0.08^b	255±12^{ab}	50.0±1.6^a

Note: Lower letters after the values represent significant differences ($p \leq 0.05$).

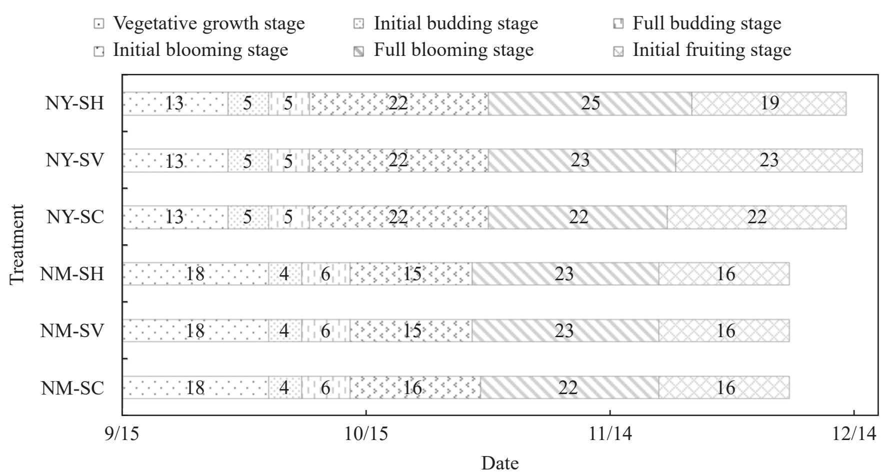
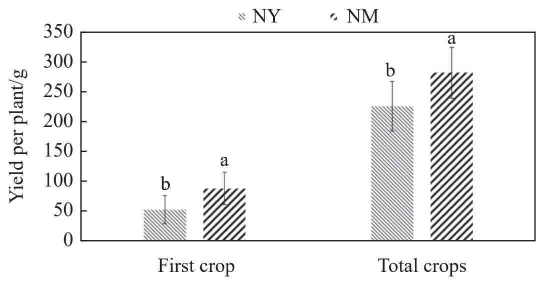


Figure 4 Effect of nutrient solution formula adjustment on strawberry phenological stage

3.5 Fruit yield

The NM treatment had a significant effect on the total fruit yield of strawberry (Figure 5). A total of 3 crops of fruits were harvested for each plant during this experiment, and the total fruit yield of per plant in NM treatments was significantly higher than that in NY treatments. The yield of the first crop and total crops of strawberry grown on NM treatment applied with the modified strawberry nutrient solution was 89 g and 282 g, which were 65% and 25% higher than that of the control treatment irrigated with Yamasaki strawberry nutrient solution.



Note: Lower letters above the data represent significant differences ($p \le 0.05$).

Figure 5 Effect of nutrient solution formula adjustment on fruit yield of per plant of strawberry

3.6 Fruit quality

Substrate had no significant effect on strawberry quality, but nutrient solution, nutrient solution and substrate coupling had a significant effect on strawberry quality. Compared with other treatments, the average weight of single strawberry fruit from NY-SV and NM-SH treatments was lower and the firmness was higher significantly (Table 5). The sugar-acid ratios of strawberries from NM-SH and NY-SV treatments were 11.6 and 10.7, respectively, which were significantly higher than others. The vitamin C contents of strawberry fruits from NM-SH and NY-SV treatments were significantly higher than others, which were 74.1 mg/100g and 65.7 mg/100g, respectively, but there were no significant differences in soluble solid contents among the different treatments.

Table 5 Effect of nutrient solution formula and substrate on the first crop quality of strawberry

Treatment	Average weight of single fruit/g	Firmness/ $kg \cdot cm^{-2}$	soluble solids content/%	Sugar-acid ratio	Vitamin C content/ $mg \cdot 100g^{-1}$
NY-SH	31.3 ± 2.5^{a}	1.33 ± 0.10^{b}	9.0 ± 0.4^{ab}	7.5 ± 1.7^{bc}	55.2 ± 3.4^{bc}
NY-SV	22.1 ± 0.6^{b}	1.77 ± 0.18^{a}	10.7 ± 0.9^{a}	11.5 ± 1.8^{a}	65.7 ± 5.7^{ab}
NY-SC	29.2 ± 3.6^{a}	1.41 ± 0.08^{b}	8.6 ± 0.7^{b}	8.1 ± 3.1^{b}	46.1 ± 11.5^{c}
NM-SH	20.3 ± 2.4^{b}	1.77 ± 0.21^{a}	10.2 ± 2.7^{a}	10.6 ± 4.2^{a}	74.1 ± 14.9^{a}
NM-SV	29.7 ± 5.0^{a}	1.30 ± 0.07^{b}	8.5 ± 0.7^{b}	6.5 ± 0.8^{c}	50.9 ± 9.0^{c}
NM-SC	28.4 ± 4.7^{a}	1.38 ± 0.18^{b}	8.9 ± 0.7^{ab}	9.6 ± 1.3^{ab}	58.8 ± 5.7^{b}
Nutrient solution	*	*	NS	*	*
Substrate	NS	NS	NS	NS	NS
Nutrient solution×Substrate	*	*	NS	*	*

Note: * indicates significant differences ($p<0.05$), NS indicates no significant differences.

4 Discussion

4.1 Substrate chemical properties

Substrate pH affects the form and effective content of nutrients in the rhizosphere. The suitable substrate pH for strawberry root growth was 5.8-6.5, while the substrate with a pH higher than 7.5 would inhibit the growth of strawberry plants[31]. Increasing the NO_3^--N/NH_4^+-N at the flowering and fruiting stage was due to prevent pH from falling too fast; decreasing the NO_3^--N/NH_4^+-N at the fruit expanding stage was due to the increase of the number of leaves between the first and second inflorescence, which was the vegetative growth begin of the second crop. According to the pH changes of the substrates, adjusting the NO_3^--N/NH_4^+-N can maintain the pH stability. The substrate pH in each treatment was almost within the suitable acid-base range for strawberry growth and development and showed a slowly decreasing trend as the growth and development stages changed. The range of NM-SH substrate pH showed at the least degree, indicating that using common mixed horticulture substrate and irrigated with modified strawberry nutrient solution had better buffering.

The potential of nutrients and water in the rhizosphere was influenced by substrate EC value, and the suitable substrate EC was 0.3-1.2 mS/cm for strawberry plants, while a lower EC value will inhibit nutrient uptake and a higher EC value will inhibit water uptake[31]. This can be observed in Figure 2b, except for NY-SV, in the other treatments were all in the range of 0.4-1.2 mS/cm, indicating that strawberry plants were grown in a suitable substrate rhizosphere.

Although the alkali-soluble organic matter content under SC treatment was higher, strawberry plants did not absorb much. The alkali-soluble organic matter content of SH treatment decreased in the late cultivation, because the organic matter in the SH substrate was decomposed, absorbed, and utilized effectively, which could provide more nutrients for strawberry growth and development.

4.2 Photosynthetic characteristics and chlorophyll content

Plant photosynthesis was closely related to the supply of water and fertilizer[32]. At the vegetative growth stage, the stomatal conductance and transpiration rate of strawberry leaves in NM treatments were significantly higher than in NY treatments, indicating that strawberry plants in NM treatments had greater transpiration pulling force which was conducive to the absorption of mineral elements, while the differences in net photosynthetic rate and intercellular CO_2 concentration were not significant. The leaf photosynthetic capacity of strawberry plants in NM treatments was greater at the vegetative growth stage and flowering and fruiting stage, probably because the nutrient elements such as nitrogen, potassium, and calcium were involved in the photosynthetic process directly or indirectly[32]. The photosynthesis of strawberry plants was effectively promoted by supplying nitrogen, potassium, and calcium from the vegetative growth stage to the flowering and fruiting stage. An increase in chlorophyll content was beneficial for enhancing leaf photosynthesis, thereby improving yield and quality. SPAD values have been shown to have a direct linear relationship to extracted leaf chlorophyll content[33]. At the fruit expanding stage, the maximum SPAD value of strawberry plant in the NM-SH treatment was higher than in other treatments, which indicated that the NM-treated strawberry plants absorbed more nitrogen, and nitrogen absorption was directly related to chlorophyll content in leaves[34,35].

4.3 Phenological stage

The greater precocity of the strawberry allows advantages, such as the anticipation of the fruit supply to the consumer market, allowing a better price for growers per kg of fruit produced[36,37] (Figure 4). Strawberry plants entered the reproductive growth later but entered the full fruiting stage earlier, combined with the rapidly available potassium content, photosynthetic characteristics and morphology changes of strawberry plants (Figures 2 and 3, and Table 4), this may be because the better K absorption of strawberry plants under the NM treatment makes strawberry plants have more vigorous and longer vegetative growth, and better vegetative growth provides the possibility for strawberry plants to enter the peak fruit harvest stage earlier. The cultivation substrate had no significant effect on the phenological stage of strawberry, combined with the previous study, this may be due to the effect of substrate on flowering time was genotype-dependent in strawberry such that flowering of 'Ssanta' showed less correlation with the substrate[38]. The results showed that adjusting the nutrient solution formula at the growth and development stages could advance the strawberries' maturity stage, bring them to market earlier, and add their economic value accordingly.

4.4 Fruit yield

The substrate had no significant effect on the first crop and total crops yield of per strawberry plant, this may be because the physical properties of substrates are similar, as listed in Table 1, and the pH of substrate remained within the appropriate range for strawberry growth and development. Although the content of alkali-soluble organic matter under the SC treatment was higher, it was not completely absorbed by strawberry, as shown in Figure 2c. But the nutrient solution formula had a significant effect on the first crop and total crops yield of per strawberry plant, this is probably because the pH of substrate under the NM treatment was stable, and it was always stable in the suitable range of strawberry. In addition, the NM treatment increased the K/Ca ratio at the fruit expanding stage, and the higher K/Ca ratio could improve fruit yield to the greatest extent, which agreed with Khalil[39] and Lieten[40].

4.5 Fruit quality

The nutritional value of strawberry fruits is an important index to evaluate the fruit quality, and directly affects the economic benefits of strawberry production. The taste of strawberry fruit is closely related to its sugar-acid ratio, and the content of vitamin C is an important embodiment of strawberry antioxidant capacity[41]. Substrate had no significant effect on strawberry quality, but nutrient solution, nutrient solution and substrate coupling had a significant effect on strawberry quality. The nutrient solution formula adjustment probably supplemented potassium for strawberry at the flowering and fruiting stage and fruit-expansion stage, which promoted the process of converting photosynthetic starch into sugar and increased fruit sweetness. In addition, higher concentration of potassium can also improve the vitamin C content of strawberry fruits, which is consist with Tohidloo[42].

5 Conclusions

This study presented a modified strawberry nutrient solution formula based on growth stage and used in substrate-cultivated strawberries in the greenhouse. The results showed that the nutrient solution formula adjustment at all growth and development stages fulfilled the requirement of nitrogen and calcium in substrate-cultivated strawberries at the vegetative growth stage and the requirement of potassium at the flowering and fruiting stage and fruit expanding stage, which advanced 'Ssanta' strawberries by one week into the full fruiting stage and improved the first crop yield and total crops yield of per plant by over 20%. The pH change range of common mixed horticulture substrate irrigated with the modified nutrient solution was less than 0.05 in strawberry's whole growth and development stages. The total yield per plant, sugar-acid ratio, and vitamin C content of strawberry in this treatment were 306 g, 10.6, and 74.1 mg/100g, respectively, which were significantly higher than others. It is recommended to use the horticulture substrate irrigated with the modified nutrient solution for the 'Ssanta' strawberries cultivation elevated in greenhouse.

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