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Effects of different N, P, K and Ca levels on tomato yield, quality and fertiliser use efficiency

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Abstract: The experiment aimed to obtain a quadratic regression mathematical model of the comprehensive evaluation score of yield, quality, and four macroelements (N, K, P and Ca). The suitable nutrient solution was chosen and verified *via* computer simulation of the model and the highest comprehensive score in all treatments. Results showed that P, K and Ca had a positive effect on the comprehensive evaluation value of tomato, whereas N showed a negative effect. The optimal formula calculated using the regression equation could promote high-yield and high-quality tomato. The single-plant yield, soluble protein, vitamin C, total sugar, lycopene, and elemental utilisation of K and Ca in the tomato were 13.93, 78.95, 3.29, 20.98, 51.91, 16.69 and 24.14% higher than those in the special formula treatment of Japanese Yamazaki tomato, respectively. In summary, the optimal nutrient solution formula of tomato cultivation was obtained, in which the N, P, K and Ca levels were 24.83, 4.50, 9.49 and 5.73 mmol/L, respectively.

Keywords: *Solanum lycopersicum* L.; soilless cultivation; vegetable management; comprehensive analysis; greenhouse

Greenhouses have become the most important agricultural structures in China (Du et al. 2015), where excessive fertilisation is common (Fan et al. 2014). Excessive fertilisation does not improve the yield and quality of crops, but causes the deterioration of the physical and chemical properties of the soil and increases soil environmental degradation (Kuscu et al. 2014). Organic substrate cultivation is an ecological and efficient cultivation model that can reuse agricultural wastes and effectively solve the problem of soil environmental degradation (Martinez-Ruiz et al. 2017, Kraska et al. 2018). Substrate-bag culture, one of the most important forms of organic substrate cultivation, means that the plants are grown in a plastic bag containing a solid substrate (Zhang and He 2006). This method has the advantages of avoiding continuous cropping obstacles, reducing pests and diseases, and increasing crop yields (Qu et al. 2019).

N, P and K are important nutrient elements in crop growth and development, they increase crop yield and quality by participating in many physiological processes (Tavallali et al. 2017, Ierna and Mauromicale 2018). Ca is closely related to tomato fruit quality, and Ca deficiency can lead to blossom-end decay and fruit cracking, exogenous Ca application can

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improve the disease resistance of tomato (Saure 2014). At present, many reports are available on the effects of different nutrient couplings on tomato growth, yield, and physiological metabolism under soil cultivation conditions (Liu et al. 2012, Wang and Xing 2017, Chamurliev et al. 2019).

Tomato is one of the most important vegetables in the world, it is delicious and is an important source of essential minerals, vitamins, and antioxidants for human health (Tavallali et al. 2017). At present, most of the nutrient solutions used in tomato substrate-bag culture are based on hydroponic conditions. The element concentration of traditional tomato nutrient solution formula must be adjusted, and the special nutrient solution formula of tomato that is suitable for substrate-bag culture conditions must be explored.

Therefore, the present study comprehensively evaluated and analysed the yield and quality of tomato under substrate-bag culture conditions. The secondary regression mathematical model was established with comprehensive scoring value and N, P, K and Ca elements. The optimal element combination was determined by the model and verified in the field. The nutrient solution formula suitable for tomato substrate-bag culture was then obtained, which provided the basis for improving the quality and high yield of tomato.

MATERIAL AND METHODS

Experimental site. The experiment was carried out during the spring seasons (March to July) of 2018 and 2019 in an asymmetric long-span plastic greenhouse located at Yangling, Shaanxi province, China (34°28'N, 108°07'E). During the experimental period, the daily average temperature, average daily night temperature, and relative humidity of the air in the plastic greenhouse were 15.4–36.1 °C, 10.8–25.4 °C and 34.4–92.8%, respectively. The daily average length of sunshine was 11–13.5 h.

Plant material and growth conditions. Tomatoes cv. Burberry (large fruit size and high yield, suitable for early spring and autumn extension cultivation in the greenhouse) were used in this study. Seedlings of similar appearance were transplanted into substrate bags (three seedlings per bag) when the fourth true leaves were completely expanded. Each substrate bag had approximate dimensions of 1.00 × 0.20 × 0.16 m (length × width × height) and contained 27 L of the cultivation substrate. The basic physical and chemical properties of the cultivation substrate are as follows: available N – 1 903.78 or 1 685.28 mg/kg; available P – 99.41 or 71.27 mg/kg; available K – 2 988 or 3 467.44 mg/kg; exchange Ca – 3 434.72 or 4 871.27 mg/kg; organic matter – 185.42 or 210.54 g/kg; pH – 7.28 or 6.81; and electrical conductivity (EC) – 2.05 or 2.36 mS/cm (spring 2018 or 2019).

Experimental design and treatments. Four-factor and five-level quadratic orthogonal rotation combination design (1/2) was used to set up the nutrient solution formula. A total of 23 treatments were conducted (Tables 1 and 2).

The optimal combination calculated using the regression equation (marked as A) and the optimal formula selected in the optimal formulation selection experiment (marked as B) were compared with the Japanese Yamazaki tomato special formula (CK) for verification.

Six cultivation bags were placed in one line, and two lines were planted for each treatment per repeat. Nutrient solution management was detailed in Table 3 during the experimental period.

Measurements of plant parameters. Five tomato plants were randomly selected for each treatment to count the yield. The fruit quality of tomato with full maturity in the third panicle was determined. The soluble protein content was measured using Coomassie Brilliant Blue (Matsuda and Kubota 2010). The soluble reducing sugar content was measured *via* thermal titration with Fehling's reagent. The soluble

Table 1. Variable standard coding value of different factors in the growth period of tomato

Variation		Code level				
		–1.682	–1	0	1	1.628
N	(mmol/L)	9	13.66	20.5	27.34	32
P		0.5	1.31	2.5	3.69	4.5
K		4	5.62	8	10.38	12
Ca		2.5	3.82	5.75	7.68	9

–1.682, –1, 0, 1 and 1.682 represent under the arm, lower level, zero level, upper level, and star on the arm, respectively

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Table 2. Test factor coding combination and experimental design

Treatment	Variation value of the treatment			
	N	P	K	Ca
	(mmol/L)			
T1	27.34 (1)	3.69 (1)	10.38 (1)	7.68 (1)
T2	27.34 (1)	3.69 (1)	5.62 (–1)	7.68 (1)
T3	27.34 (1)	1.31 (–1)	10.38 (1)	3.82 (–1)
T4	27.34 (1)	1.31 (–1)	5.62 (–1)	3.82 (–1)
T5	13.66 (–1)	3.69 (1)	10.38 (1)	3.82 (–1)
T6	13.66 (–1)	3.69 (1)	5.62 (–1)	3.82 (–1)
T7	13.66 (–1)	1.31 (–1)	10.38 (1)	7.68 (1)
T8	13.66 (–1)	1.31 (–1)	5.62 (–1)	7.68 (1)
T9	9.00 (–1.68)	2.50 (0)	8.00 (0)	5.75 (0)
T10	32.00 (1.68)	2.50 (0)	8.00 (0)	5.75 (0)
T11	20.50 (0)	0.50 (–1.68)	8.00 (0)	5.75 (0)
T12	20.50 (0)	4.50 (1.68)	8.00 (0)	5.75 (0)
T13	20.50 (0)	2.50 (0)	4.00 (–1.68)	5.75 (0)
T14	20.50 (0)	2.50 (0)	12.00 (1.68)	5.75 (0)
T15	20.50 (0)	2.50 (0)	8.00 (0)	2.50 (–1.68)
T16	20.50 (0)	2.50 (0)	8.00 (0)	9.00 (1.68)
T17	20.50 (0)	2.50 (0)	8.00 (0)	5.75 (0)
T18	20.50 (0)	2.50 (0)	8.00 (0)	5.75 (0)
T19	20.50 (0)	2.50 (0)	8.00 (0)	5.75 (0)
T20	20.50 (0)	2.50 (0)	8.00 (0)	5.75 (0)
T21	20.50 (0)	2.50 (0)	8.00 (0)	5.75 (0)
T22	20.50 (0)	2.50 (0)	8.00 (0)	5.75 (0)
T23	20.50 (0)	2.50 (0)	8.00 (0)	5.75 (0)

sugar content was measured using the anthrone method (Liu et al. 2013). Vitamin C and organic acid were determined in accordance with the method of Bona et al. (2015). Nitrate and lycopene contents were determined in accordance with the methods of Garcia-Robledo et al. (2014) and Bona et al. (2017), respectively.

At telophase of the fruiting stage, five tomato plants for each treatment were collected to measure the element contents. The total N, total K, total Ca, and total Mg in the leaf, shoot, root, and fruit were determined following the method of Qu et al. (2019).

Related index calculation and statistical analysis. Element (N, P, K and Ca) use efficiency (%) = (fertilisation treatment of nutrient uptake – no fertilisation treatment of nutrient uptake)/amount of fertiliser (Mon et al. 2016) (1):

Each index was normalised in accordance with Eq. 2, and a new decision matrix $Y = (y)_{n \times m}$ was obtained (n – number of treatments; m – number of indicators).

$$y_{ij} = \frac{x_{ij}}{\sum_{i=1}^{n} x_{ij}} \tag{2}$$

In Eq. 2, x_{ij} – No. j original index of the No. i treatment.

The information entropy (E_j), information entropy redundancy (D_j), and weight matrix (W_j) were obtained in accordance with Eqs. (3), (4), and (5).

$$E_j = -\frac{1}{\ln n} \sum_{i=1}^{n} y_{ij} \ln y_{ij} \tag{3}$$

$$D_j = 1 - E_j \tag{4}$$

$$W_j = \frac{D_j}{\sum D_j} \tag{5}$$

The comprehensive evaluation value (y_i') of each treatment was calculated in accordance with the linear weighted model (6):

$$y_i' = \sum_{j=1}^{m} W_j x_{ij} \tag{6}$$

The experimental design of the optimal formula selection experiment was obtained using the Document

Table 3. Nutrient solution management for the experiment

Days after planting (days)	The daily supply of nutrient solution per tomato plant (L)		
	treatment A	treatment B	CK
25	0.5	0.5	1.0
50	1.0	1.0	2.0
80	1.5	1.5	3.0
120	0.5	0.5	1.0

For the CK during verification experiment, the concentrations of N, P, K and Ca were 7.67, 0.67, 4 and 1.5 mmol/L. All treatment trace element dosages were the same: EDTA-NaFe (25 mg/L); H_3BO_3 (2.86 mg/L); $MnSO_4 \cdot H_2O$ (1.61 mg/L); $ZnSO_4 \cdot 7\ H_2O$ (0.22 mg/L); $CuSO_4 \cdot 5\ H_2O$ (0.08 mg/L) and $(NH_4)6Mo_7O_{24} \cdot 4\ H_2O$ (0.02 mg/L)

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Processing System (DPS) 7.05, and the quadratic orthogonal rotation model was established. Statistical Product and Service Solutions (SPSS) 20.0 was used for data processing and variance analysis. Excel 2010 was used for mapping, and the *LSD* (least significant difference) method ($P < 0.05$) was used for multiple comparisons.

RESULTS AND DISCUSSION

Comprehensive evaluation and analysis of tomato yield and quality. The comprehensive scores of treatment T12 and T4 were the highest and the lowest, respectively, indicating that T12 is most favourable for obtaining high yield and quality tomato, whereas T4 was the most unfavourable (Table 4).

Establishment of the regression equation. The regression model among yield, quality comprehensive score (Y), and N (X_1), K (X_2), Ca (X_3), Mg (X_4) contents were obtained:

$$Y = 0.0482 - 0.0003X_1 + 0.0017X_2 + 0.0014X_3 + 0.0005X_4 - 0.0039X_1^2 + 0.0007X_2^2 - 0.0024X_3^2 - 0.0025X_4^2 + 0.0022X_1X_2 + 0.0025X_1X_3 - 0.0009X_1X_4 \quad (8)$$

In model (8), the multiple correlation coefficient $R^2 = 0.9081$, $F = 5.64 > F_{0.05} = 0.0013$, and the regression relationship reached a very significant level. The regression coefficient test showed that the interactions between N and P and between N and K were positive, whereas that between N and Ca was negative. P, K and Ca had a positive effect on the comprehensive evaluation value of tomato, whereas N had a negative effect (Table 5). And these results were consistent with those of Corrêa et al. (2018) and Wang et al. (2019). However, a previous study has shown a negative interaction between N and K on mung bean yield (Yin et al. 2018), it may be due to differences in cultivated crops and evaluation indicators.

Table 4. Dependence degree of the evaluation factors and indexes for a comprehensive evaluation in different processing units

Evaluation unit	Single plant yield	Soluble protein	Vitamin C	Reducing sugar	Total sugar	Lycopene	Nitrate	Organic acid	Comprehensive evaluation value	Rank
T1	0.0474	0.0485	0.0392	0.0429	0.0528	0.0609	0.0583	0.0403	0.0484	2
T2	0.0342	0.0448	0.0277	0.0309	0.0302	0.0476	0.0616	0.0384	0.0372	21
T3	0.0381	0.0445	0.0377	0.0345	0.0430	0.0303	0.0493	0.0502	0.0388	17
T4	0.0273	0.0493	0.0299	0.0199	0.0347	0.0374	0.0546	0.0581	0.0324	23
T5	0.0340	0.0493	0.0311	0.0308	0.0293	0.0411	0.0468	0.0477	0.0360	22
T6	0.0434	0.0482	0.0426	0.0393	0.0494	0.0384	0.0495	0.0470	0.0434	13
T7	0.0434	0.0465	0.0382	0.0393	0.0425	0.0470	0.0524	0.0451	0.0438	12
T8	0.0363	0.0486	0.0441	0.0329	0.0360	0.0502	0.0396	0.0489	0.0391	16
T9	0.0377	0.0452	0.0363	0.0342	0.0358	0.0316	0.0438	0.0413	0.0373	20
T10	0.0354	0.0487	0.0382	0.0320	0.0353	0.0318	0.0567	0.0563	0.0381	19
T11	0.0440	0.0333	0.0566	0.0398	0.0569	0.0495	0.0587	0.0449	0.0468	10
T12	0.0537	0.0426	0.0394	0.0487	0.0582	0.0929	0.0394	0.0490	0.0545	1
T13	0.0391	0.0393	0.0312	0.0354	0.0372	0.0471	0.0519	0.0505	0.0405	15
T14	0.0452	0.0383	0.0312	0.0409	0.0415	0.0475	0.0386	0.0508	0.0433	14
T15	0.0452	0.0362	0.0383	0.0410	0.0433	0.0436	0.0485	0.0560	0.0447	11
T16	0.0395	0.0384	0.0421	0.0358	0.0480	0.0328	0.0319	0.0474	0.0387	18
T17	0.0509	0.0425	0.0566	0.0603	0.0466	0.0387	0.0311	0.0325	0.0481	5
T18	0.0510	0.0428	0.0567	0.0602	0.0465	0.0386	0.0312	0.0326	0.0482	3
T19	0.0507	0.0427	0.0565	0.0603	0.0464	0.0385	0.0312	0.0326	0.0480	8
T20	0.0509	0.0427	0.0565	0.0602	0.0465	0.0386	0.0312	0.0326	0.0481	7
T21	0.0510	0.0425	0.0566	0.0602	0.0465	0.0386	0.0312	0.0325	0.0482	4
T22	0.0509	0.0425	0.0566	0.0602	0.0466	0.0386	0.0312	0.0326	0.0481	6
T23	0.0506	0.0426	0.0566	0.0603	0.0466	0.0386	0.0311	0.0326	0.0480	9

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Table 5. Significance test for the regression coefficients of the regression equation

Factor	Regression coefficient	Standard coefficient	*t*-value	*P*-value
X_1	–0.0003	–0.04	0.51	0.6211
X_2	0.0017	0.25	2.87	0.0186**
X_3	0.0014	0.20	2.33	0.0448*
X_4	0.0005	0.07	0.82	0.4345
X_1X_1	–0.0039	–0.60	6.87	0.0001**
X_2X_2	0.0007	0.11	1.25	0.243
X_3X_3	–0.0024	–0.37	4.23	0.0022**
X_4X_4	–0.0025	–0.38	4.36	0.0018**
X_1X_2	0.0022	0.24	2.80	0.0208**
X_1X_3	0.0025	0.28	3.19	0.0111**
X_1X_4	–0.0009	–0.10	1.13	0.2869

LSD's multiple range tests on the significance of the regression coefficient *via* the DPS 7.05 data processing system. $^{*}P < 0.01$; $^{**}P < 0.05$

The best combinations were X_1 (N) = 0.64, X_2 (P) = 1.68, X_3 (K) = 0.63 and X_4 (Ca) = –0.01. The best combination obtained by the regression equation was not included in the 23 experimental treatment combinations involved. The combination obtained must be further verified.

Effects of different formulations on tomato yield and quality. Compared with those of CK, the single plant yield, soluble protein, vitamin C, total sugar, and lycopene in treatment A were significantly increased by 13.93, 78.95, 3.28, 20.98 and 51.91%, respectively. The contents of soluble protein and lycopene in treatment B were significantly higher by 21.05% and 51.56%, respectively, than those in CK (Table 6). The proper increase in N and K supply was beneficial to the increase in crop yield (Ucar et al. 2017), which may be the reason for the highest yield of treatment A in the three treatments. The soluble protein content of treatment A was significantly higher than that of treatment B, and the soluble protein content in treatment B was significantly higher than that in CK. In addition, the vitamin C content in treatment A was significantly higher than that in CK, which was consistent with the conclusion that the content of soluble protein and vitamin C in vegetables could be increased by properly increasing the level of N supply (Simonne et al. 2007). The increase in K supply is beneficial to the increase in lycopene content (Almeselmania et al. 2010), which may be the reason why the lycopene content in treatments A and B was higher than that in CK. The organic acid content in treatments A and B was lower than that in CK, possibly due to their N and K contents being higher than those in CK, which was consistent with the results of Wang et al. (2019).

Effects of different formulations on element utilisation efficiency in tomato plants. The utilisation efficiency of N in tomato was the highest, whereas that of Ca was the lowest (Figure 1), possibly because Ca is transported *via* transpiration in the xylem, the transpiration of the tender part and the fruit is small, and the mobility of Ca is poor, making it difficult to transport Ca to the tender part and the fruit (White and Broadley 2003) and be utilised. The highest absorption efficiency of K was found in treatment A, which was 8.30% and 16.69% higher than that of treatment B and CK, respectively. The absorption efficiency of Ca in treatment A was higher than the absorption in treatment B and CK, by 11.88% and 24.14%, respectively (Figure 1).

In conclusion, the order of the influence of each element on the comprehensive evaluation score of tomato quality and yield was as follows: P > K > Ca > N, with P, K and Ca having a positive effect on tomato comprehensive evaluation score and N having a negative effect. The nutrient solution formula selected by the model is beneficial for promoting the high quality and high yield of bag-cultured tomato and improving the absorption efficiency of K and Ca. Therefore, the recommended N, P, K and Ca concentrations for the nutrient solution formula in spring facility tomato production are 24.83, 4.50, 9.49 and 5.74 mmol/L, respectively.

Table 6. Effects of different formulas on the yield and quality of tomato

Treatment	Single plant yield (kg/plant)	Soluble protein (mg/g)	Vitamin C (mg/100 g)	Total sugar (%)	Lycopene (μg/g)	Organic acid (%)
A	2.78 ± 0.04^{a}	0.34 ± 0.006^{a}	42.21 ± 0.24^{a}	4.21 ± 0.05^{a}	87.68 ± 3.55^{a}	1.72 ± 0.06^{b}
B	2.57 ± 0.13^{ab}	0.23 ± 0.006^{b}	41.88 ± 0.42^{ab}	3.58 ± 0.07^{b}	87.48 ± 4.32^{a}	1.71 ± 0.03^{b}
CK	2.44 ± 0.08^{b}	0.19 ± 0.007^{c}	40.87 ± 0.31^{b}	3.48 ± 0.02^{b}	57.72 ± 1.43^{b}	1.92 ± 0.03^{a}

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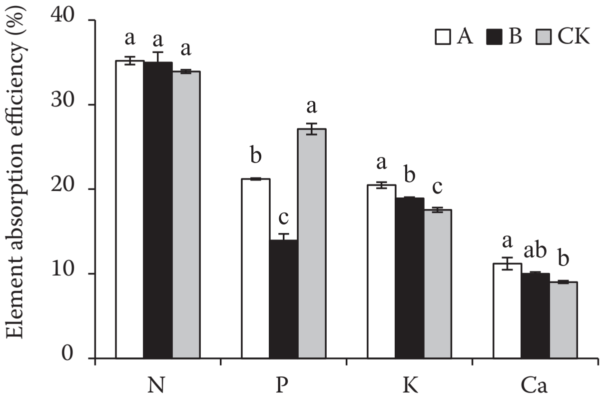

Figure 1. Effects of different formulas on the element absorption efficiency of tomato. Treatment A (N, P, K and Ca concentrations of 24.83, 4.50, 9.49 and 5.73 mmol/L, respectively) is the optimal combination selected in accordance with the regression model. Treatment B (N, P, K and Ca concentrations of 20.50, 4.50, 8.00 and 5.75 mmol/L, respectively) has the highest comprehensive evaluation value of the optimal formula selection experiment. CK is the Yamazaki tomato nutrient solution formula (N, P, K and Ca concentrations of 7.67, 0.67, 4.00 and 1.50 mmol/L, respectively). Mean values are shown and error bars represent the standard error of the mean (n = 4). Different letters at each sampling data indicate significant differences between treatments in accordance with *LSD*'s (least significant difference) multiple range test at $P < 0.05$ level

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