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Full Length Article

Tomato Nutritional Quality Indexes under Various Biogas Slurry and Irrigation Schemes

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Abstract

The tomato (*Lycopersicum esculantum* Mill.) comprehensive nutritional quality evaluation index was evaluated in present study with biogas slurry irrigation along with the analysis of its response to the supply of water and fertilizer. Three crop-pan coefficients (0.6, 0.8 and 1.0, respectively) and four biogas slurry concentrations (volume percentages of 0, 12, 15 and 20%, respectively) were used under field conditions. Six single nutritional quality indexes including soluble solids, soluble total sugar, titrate acid, the sugar acid ratio, vitamin C and soluble protein were monitored. On the basis of analytic hierarchy process and the variation coefficient method, the combination weighing method of game theory was adopted to obtain weight of each tomato single nutritional quality. Results showed in the descending order of vitamin C>soluble protein>the sugar acid ratio>soluble sugar>soluble solids>titrate acid. Tomato comprehensive nutritional quality indexes were obtained by technique for order preference by similarity to ideal solution. On this basis, mathematical models were established by stepwise regression analysis to analyze the response to different water and fertilizer factors. Results showed that the response of tomato comprehensive nutritional quality to each water and fertilizer factor was in a descending order of the irrigation amount>nitrogen rate> phosphorus rate> potassium rate. When other factors were at the intermediate level, the changing between tomato comprehensive nutritional quality and P, N and K rates and the irrigation water amount were all fitted in quadratic curves. According to the optimum solution of the established equation, the P, K and N rates of 2.24, 6.05 and 5.78 g and water amount of 25 L irrigated can reach the best comprehensive nutritional quality of tomato. In conclusion, application of biogas slurry concentration (20%) and irrigation amount of 0.8AE_p was the treatment most close to the optimum among all observed treatments.

Keywords: Biogas slurry; Tomato (*Lycopersicum esculantum* Mill.); Comprehensive nutritional quality; Stepwise regression analysis

Introduction

Tomato (*Lycopersicum esculantum* Mill., Fam.: Solanaceae) has been preferred by many consumers due to its delicious flavor and rich nutritional characteristics (Li, 2006). Along with gradual modernization of fresh vegetable market, besides vegetable type, consumers pay more attention to its quality (Ruiz-Altisent *et al.*, 2006). During the cultivation, many factors influence the vegetable quality. Of which, genetic factors and growth environment are the main to affect tomato quality (Agbna *et al*., 2017). Among environmental factors, water and nutrients are found as key factors for the growth and yield of tomato fruits (Dorais *et al*., 2002). Thus, reasonable water and fertilizer management could be considered as key steps to enhance not only tomato quality but also its yield. In the production of greenhouse vegetables, inappropriate use of water and fertilizer would not only deteriorate the yield and quality but also pollute the surface water and soil environment (Mohammad and Mazahreh, 2003). On the other hand, the applied amount of water and fertilizer and their application mode and frequency are the principal causes which could affect vegetable quality (Agbna *et al*., 2017). Recent studies carried out mainly focused on single factor water and fertilizer including their effects on nutritional quality of vegetables. Previous studies reveal that the effect of integrated application of water and fertilizer and/or water and biogas slurry on nutritional quality of crops during crop growing period is still scarce (Ju, 2009; Wang *et al*., 2011; Xie *et al*., 2011).

High market value of tomato crop is based on its exterior (size, shape and color), flavor (soluble solid material, soluble sugar and organic acid), nutritional

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(lycopene, soluble protein and vitamin C), storage and transportation qualities (hardness). Thus, the quality of tomato happens to be a comprehensive concept and is based on the result of interaction with different single nutritional quality (Davies *et al*., 1981; Li *et al*., 2019). Each single quality had different evaluation index. Besides, different quality indexes interrelate to some extent. Now a day, tomato comprehensive quality is determined by the importance of each characteristic quality (Wang *et al*., 2011). Therefore, tomato quality should be addressed considering not only the weight of each single quality but also the requirement of consumers. In the recent time, frequently used weight determination for tomato included subjective (analytic hierarchy process), objective (the entropy weight method, eigenvector, the variation coefficient method) and comprehensive weighing *i.e*., three assembly models of game theory, team and group (Chi *et al*., 2008). Analytic hierarchy process (AHP) meant to disable the complex problem into composition factors according to targets which were needed to be accomplished and to analyze problems qualitatively and quantitatively without considering difference of observed values. Thus, it was a subjective weighing method (Vaidya and Kumar, 2006; Zhang *et al*., 2011).

The variation coefficient method obtained weight of each index according to variability degree of observed weight values under specific conditions. But some research showed that it was impossible to confirm the importance of index according to weight values (Ye, 2010). However, the technique for order preference by similarity to ideal solution (TOPSIS) is usually applied to establish estimation in multi-objective space. This could also be used further, to evaluate the realization possibility of target according to the distance between the determined target and positive or negative ideal solution (Wang and Lee, 2007; Lei *et al*., 2016). Based on this concept, field plot trials selecting tomato as trial crops by setting different irrigation water amount and concentration of biogas slurry were adopted in the present research. Six indexes including soluble solids, soluble sugar, titrate acid, sugar acid ratio, soluble protein and vitamin C were considered. Assembly model of game theory was adopted to conduct organic treatment of nutritional quality index weights acquired by the AHP method and the variation coefficient method (Chi *et al*., 2008). Then, balanced and single nutritional quality weight with biogas slurry irrigation was obtained. In the meantime, comprehensive nutritional quality of tomato was evaluated in detail with TOPSIS method, which provided theoretical support for the establishment of the efficiency and quality enhancement mode with biogas slurry.

Materials and Methods

Experimental Site

The experimental sites for the present research, where the integration of available facilities, study crop, water and fertilizers were carried out are named Greenish and Weiling County, Qilihe District, Lanzhou City of the People's Republic of China (Fig. 1). The geographical coordinates of the experimental sites are 36^{o}03' N and 103^{o}40' E and situated at an altitude 1872 m MSL. The weather was dry and with sufficient sunlight but little rain. Average annual temperature was 8.9ºC with no frost period of 150 d. Average annual precipitation was 310.5 mm mainly concentrated from July to September. Average annual evaporation amount was 1158.0 mm. All the experiments were carried out in a daylight greenhouse, measured 50.0×10.5×4.0 m (L×W×H).

Experimental Material

The tomato cultivar "No. 3 of Hongbao" was a top grade precocious and belonged to large, red and hard fruit type. It was planted on March 12, 2017, permanently with seedling of four big leaves and one heart and uprooted after harvest of tomatoes on July 30, 2017 *i.e*., the end of the experiment.

The soil type of the experimental fields belongs to loam clay with contents of sand, silt and clay at 38.92, 21.06 and 40.02%, respectively. Average unit weight of soil in 1 m soil layer was 1.40 g/kg with field water content of 25% (weight water fraction). Nutritional condition of the soil before crop planting were as follows: average organic matter content 9.1 g/kg in 0–40 cm layer, total N, P and K rates were 0.575, 1.531 and 1.586 g/kg, respectively. Before the commencement of trials, the recorded soil pH was 8.05.

The Biogas Slurry

The biogas slurry used in the experiment was collected from the biogas tank with normal fermentation and gas production in 'Gansu Hesitan Cow' breeding center situated in Huazhuang County, Lanzhou City. Before application of the slurry in the experimental fields, it was allowed standing and aeration for two months so that the physicochemical properties become stabilized. The biogas engineering used cow dung as fermentation material with pH of original biogas slurry as 7.23. Nutritional status of organic matter, total N, total P and total K contents were 10.75, 1.036, 0.533 and 1.186 g/L, respectively. Relatively large suspended particles present in the biogas slurry were filtered by four layers of gauze (32 mesh).

Experimental Design

12 treatments were set up in the experiment, including: a orthogonal experiment with three biogas slurry (BS) concentrations and three irrigation amounts consisting of nine treatments. Three biogas slurry concentrations were: 20, 15 and 12%. Three irrigation amounts were 0.6, 0.8 and 1.0 AE_p, where E_p is the amount of evaporation in two irrigation intervals determined by 20 cm standard

evaporating dish; *A* is plot area, 30 ×50 cm. Three controls, CK1, CK2 and CK3 were irrigated by pure water with irrigation amount of 0.6, 0.8 and 1.0 AE_p and no biogas slurry, respectively (Table 1). The distance between individual tomato plants was 30 cm with a row spacing of 50 cm. There were protective row around the plot. To avoid mutual permeation of water and fertilizer between plots, which would influence the accuracy of the trial, the adjacent two plots were separated from each other using plastic cloth of 1 m depth. The trial utilized hole irrigation with the biogas slurry. The hole was set at the position which had a 10 cm distance to crop along the ridge. There were holes at both sides of each crop with a diameter of 7 cm and a depth of 5 cm. The irrigation frequency was 2/d. There were 12 treatments, each of which had three replicates. The resultant average was reported as result of the experiment.

Traits Determination

Sample collection: Among the second spike fruit in the maturity period, two red and mature fruits from each experimental crop were randomly selected and homogenized by juicer. The resultant homogenized tomato pulp was thus analyzed.

Indicator determination method: Soluble solids were determined by RHBO-90 Abbe refractometer (Luo and Li, 2018). Vitamin C was determined by Molybdenum blue colorimetry (Mariz-Ponte *et al*., 2018). The titrate acidity was determined by 0.1 mol/L NaOH titration method (Nadia and Michel, 2018). Total soluble sugar was determined by Anthrone colorimetry method (Zhu *et al*., 2018) and soluble protein was determined by Coomassie brilliant blue G-250 staining method.

Data Processing and Analysis

As shown in Fig. 2, comprehensive index evaluation system was established according to the AHP method. Furthermore, questionnaires of tomato nutritional quality were designed. To make sure the importance of different evaluation indexes in different hierarchies, each pair was compared in a scale of 1–9. Meantime, there were 390 consumers and 10 horticultural experts in all, who took part in the evaluation of questionnaires. A total of 315 effective questionnaires were recovered with the recovery rate of 78.8%. Results of the valid questionnaires were analyzed by excel and yaahp 0.6.0 software which was based on the AHP method. Trial data were calculated by excel using the variation coefficient and TOPSIS methods in this work. The optimization of combination coefficients and normalization of weights in combination weighing method of game theory was achieved by MATLAB 6.5 software. Accordingly, related figures and tables were drawn. Spearman correlation analysis was conducted for determining the data of tomato single quality and the treatment order determined by TOPSIS by S.P.S.S. 19.0 software. In addition, Origin 9.1 software was used for drawing figures and simulation analysis.

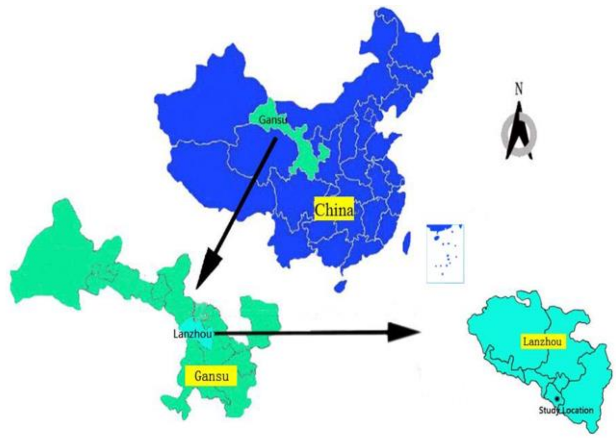

Fig. 1: Research location for biogas slurry application experiments in greenhouse

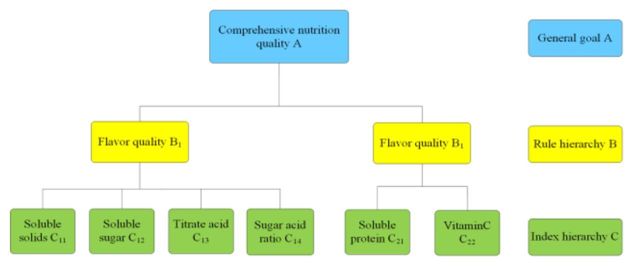

Fig. 2: Hierarchical model of tomato nutritional quality

Results

Single Nutritional Quality Index Weight by Subjective Analytic Hierarchy Process

According to the hierarchy model of tomato nutritional quality (Fig. 2) and the questionnaire results, the judgment matrix of tomato nutritional quality has been established. The results were analyzed to obtain local weights of different nutritional indexes in different hierarchies as well as corrected ultimate weight. According to ultimate weight, different single nutritional qualities of tomato were proposed in a descending order of soluble protein>vitamin C>soluble solids>the sugar acid ratio>titrate acid (Table 2). The weight of soluble protein was the largest (0.304) and titratable acid was the lowest (0.058). Combined with the hierarchy model of tomato comprehensive nutrition quality, weights of health quality (0.528) was larger than that of flavor quality (0.472) (Fig. 2).

Tomato single nutrition quality weight determination by the variation coefficient method: To guarantee both the scientific basis and rationality of tomato single nutrition quality weight, determined values of tomato

Table 1: Showing the experimental processing protocol

No.	Treatments	Amount of irrigation[1]		N rate/(g)	P rate/(g)	K rate/(g)
		Irrigation amount/(L)	Biogas slurry/(L)			
1	CK1 (0.6AE_P, water)	19.00	/	/	/	/
2	CK2 (0.8AE_P, water)	25.00	/	/	/	/
3	CK3 (1.0AE_P, water)	31.00	/	/	/	/
4	T1 (0.6AE_P, 20% BS)	15.00	3.72	3.83	1.97	4.39
5	T2 (0.8AE_P, 20% BS)	20.00	5.12	5.28	2.72	6.05
6	T3 (1.0AE_P, 20% BS)	25.00	6.31	6.53	3.36	7.47
7	T4 (0.6AE_P, 15% BS)	15.00	2.55	2.59	1.33	2.97
8	T5 (0.8AE_P, 15% BS)	20.00	3.33	3.42	1.76	3.91
9	T6 (1.0AE_P, 15% BS)	25.00	4.24	4.35	2.24	4.98
10	T7 (0.6AE_P, 12% BS)	15.00	1.93	1.97	1.01	2.25
11	T8 (0.8AE_P, 12% BS)	20.00	2.54	2.59	1.33	2.97
12	T9 (1.0AE_P, 12% BS)	25.00	3.22	3.32	1.71	3.80

Note: Amount of irrigation refers to the amount used during the whole growth period of each tomato crop, L; 0.6, 0.8 and 1.0 are the crop-pan coefficient; E_p is the amount of evaporation in two irrigation intervals, mm; *A* is plot area, 30 ×50 cm; 12, 15 and 20% BS represent the volume ratio of biogas slurry

Table 2: Pair-wise comparison matrices and weight from AHP (analytic hierarchy process)

Judgment matrix						Local weight	Ultimate weight	Consistency test parameters
General goal A-rule hierarchy B	Index	B_1		B_2		W_A	ω_A	CR=0
	B1	1.000		0.894		0.472	0.472	λ_{max}=2.000
	B2	1.119		1.000		0.528	0.528	
Rule hierarchy B1-index hierarchy C	Index	C_{11}	C_{12}	C_{13}	C_{14}	W_{B1}	ω_{B1}	CR=0.030<0.1
	C_{11}	1.000	2.212	2.896	2.453	0.446	0.210	λ_{max}=4.080
	C_{12}	0.452	1.000	1.682	0.496	0.174	0.082	
	C_{13}	0.345	0.595	1.000	0.469	0.123	0.058	
	C_{14}	0.408	2.016	2.132	1.000	0.258	0.122	
Rule hierarchy B2-index hierarchy C	Index	C_{21}		C_{22}		W_{B2}	ω_{B2}	CR=0
	C_{21}	1.000		1.356		0.576	0.304	λ_{max}=2.000
	C_{22}	0.738		1.000		0.425	0.224	

Note: C_{11}, C_{12}, C_{13}, C_{14}, C_{21} and C_{22} represent soluble solids, soluble sugar, titratable acid, sugar-acid ratio, soluble protein and vitamin C, respectively; W_A is the local weight of layer B according to layer A, and the same goes with W_{B1} and W_{B2} ; ω_A means the ultimate weight of layer B to general goal *A*, and the same with ω_{B1} and ω_{B2}; λ_{max} is the largest eigenvalue

single nutrition quality were used. The results were used to establish judgment matrix by the variation coefficient method and the index evaluation system to confirm further the determined value variability of different tomato single nutrition qualities. It can be seen that different tomato single nutrition qualities in trials were in a descending order of vitamin C>the sugar acid ratio>soluble protein>soluble sugar>soluble solids>titrate acid (Table 3). In the order, all weights of vitamin C (0.367) were the highest. Besides, all weights of titrate acid (0.043) were the lowest. There was difference between the sorting of single nutrition quality weight of this method and that confirmed by AHP method. Thus, it was necessary to analyze and treat the weights obtained by two methods further.

Tomato single nutritional quality weight determined by combination weighing method of game theory: Subjective weight u_1 and objective weight u_2 of different single nutrition qualities could be determined by the AHP method and the variation coefficient method, whereas weights of two were different. Based on the difference, basic weight sets could be established which contained the ideal weight set of u_*. In this work, u_* was obtained by assembly model of game theory. Besides, assembly model of tomato single nutrition quality weight vector was obtained as shown in Equation (1)

$$\min\left\|\sum_{j=1}^{j}\alpha_j\mu_j^T\right\|_2 \quad i=1,2; \tag{1}$$

Where α_j was linear combination coefficient.

$$\begin{pmatrix}\mu_1\mu_1^T & \mu_1\mu_2^T\\ \mu_2\mu_1^T & \mu_2\mu_2^T\end{pmatrix}\begin{pmatrix}\alpha_1\\ \alpha_2\end{pmatrix}=\begin{pmatrix}\mu_1\mu_1^T\\ \mu_2\mu_2^T\end{pmatrix} \tag{2}$$

On the basis of assembly model of game theory, combined with the differential properties of matrix, Equation 2 showed the optimized first-order derivative condition as shown in Equation 1. Combination coefficients in the trials could be obtained by Matlab software. After normalization, the optimized combination coefficients of above models were obtained and shown in Table 4. On the basis of model 1, combined with Equation 3, we get:

$$\mu^* = \sum_{i=1}^{1}\alpha_1\mu_i^T \quad i=1,2; \tag{3}$$

where α_j was linear combination coefficient.

Weight vectors of different tomato single nutrition qualities were obtained (Table 5). In trials, all weights of vitamin C were the highest and of titrate acid were the lowest. Different tomato single nutrition quality weights based on combination weighing method of game theory were in a descending order of vitamin C>soluble

Table 3: Tomato single nutritional quality weight determined by coefficient of variation method

Index	C_{11}	C_{12}	C_{13}	C_{14}	C_{21}	C_{22}
Weight	0.063	0.133	0.043	0.237	0.153	0.367

Table 4: Optimal combination coefficient based on game theory

Treatment	α_1	α_2
Calculated result	0.402	0.690
Normalized result	0.368	0.632

Table 5: Game theory assembly model to determine tomato single nutritional quality weight

Index	C_{11}	C_{12}	C_{13}	C_{14}	C_{21}	C_{22}
Weight	0.117	0.114	0.049	0.195	0.209	0.314

Table 6: Comprehensive Nutritional Quality and Sorting of Tomatoes Determined by TOPSIS Method

Treatment	C_{11}	C_{12}	C_{13}	C_{14}	C_{21}	C_{22}	d_i^+	d_i^-	A_i^*	Rack
CK1 (0.6AE_P, water)	0.075	0.067	0.070	0.071	0.081	0.081	0.022	0.019	0.498	11
CK2 (0.8AE_P, water)	0.079	0.079	0.078	0.077	0.082	0.082	0.015	0.024	0.622	10
CK3 (1.0AE_P, water)	0.075	0.009	0.086	0.085	0.085	0.083	0.034	0.012	0.181	12
T1 (0.6AE_P, 20% BS)	0.087	0.097	0.087	0.084	0.084	0.084	0.004	0.035	0.813	3
T2 (0.8AE_P, 20% BS)	0.099	0.110	0.086	0.089	0.086	0.089	0.007	0.031	0.965	1
T3 (1.0AE_P, 20% BS)	0.071	0.110	0.068	0.089	0.086	0.089	0.011	0.034	0.764	4
T4 (0.6AE_P, 15% BS)	0.083	0.091	0.086	0.084	0.083	0.083	0.004	0.035	0.752	5
T5 (0.8AE_P, 15% BS)	0.089	0.105	0.092	0.085	0.084	0.085	0.009	0.029	0.875	2
T6 (1.0AE_P, 15% BS)	0.077	0.088	0.085	0.085	0.083	0.081	0.010	0.028	0.701	6
T7 (0.6AE_P, 12% BS)	0.081	0.082	0.082	0.084	0.082	0.082	0.010	0.028	0.673	8
T8 (0.8AE_P, 12% BS)	0.080	0.080	0.078	0.082	0.082	0.082	0.011	0.026	0.647	9
T9 (1.0AE_P, 12% BS)	0.080	0.084	0.086	0.085	0.082	0.081	0.013	0.025	0.686	7
S^+	0.099	0.110	0.092	0.089	0.086	0.089				
S^-	0.071	0.009	0.068	0.071	0.081	0.081				
R	0.664*	0.727*	0.760*	0.944**	0.804**	0.788*				

Note: * and ** are significantly correlation at 0.05, and 0.01 level, respectively; *Ai** is the relative closeness; d^+ and d^- mean the weighted distances between each alternative and the optimal or inferior ideal solutions, respectively; S^+ and S^- are the optimal and inferior ideal solutions, respectively; *R* is the Spearman correlation coefficient between comprehensive quality rank and single quality index rank ($P < 0.05$); 0.6, 0.8 and 1.0 are the crop-pan coefficient; E_p is the amount of evaporation in two irrigation intervals, mm; *A* is plot area, 30 × 50 cm; 12, 15 and 20% BS represent the volume ratio of biogas slurry

protein>the sugar acid ratio>soluble sugar>soluble solids>titrate acid.

Tomato Comprehensive Nutritional Quality Index Determination

After normalization of different tomato single nutritional qualities in the trial, with determination of tomato single quality index weight by game theory assembly model as well as adoption of TOPSIS method, relative closeness degree of tomato comprehensive nutrition quality Ai* (0<Ai*<1) (Wang *et al*., 2011) could be obtained. The value was directly proportional to the tomato comprehensive nutritional quality, illustrating the effective improvement of tomato nutritional quality by this treatment. With sorting by size of A_i^*, combined with determined values of different tomato single nutrition qualities, spearman correlation analysis of different trial treatments showed that the highest A_i^* value obtained by T2 (0.8AE_P, 20%BS) treatment illustrated that it was the best among different treatments of tomato nutrition quality (Table 6). The order of A_i^* value was positively correlated with determined values of different tomato single nutrition qualities with different treatments. The order of tomato comprehensive nutritional qualities by different treatments via TOPSIS method was in accordance with the order based on single index, which could be used to analyze the influence of different supply of water and fertilizer on tomato comprehensive nutritional quality.

Influence of Single Factor on Tomato Comprehensive Nutritional Quality

When the water and fertilizer factors were within the scope of trial design, with the simulation of the evaluated values of tomato comprehensive nutritional quality, the relationship with different single factors of water and fertilizer were obtained. The variation between tomato comprehensive nutritional quality and contents of N, P, and K element in applied biogas slurry as well as irrigation amount demonstrated quadratic curves (Fig. 3a–d). In pre-growth period of tomato, with the increase of the applied amounts of water and fertilizer, trace elements contents of N, P and K in biogas slurry as well as irrigation water amount promoted tomato comprehensive nutrition quality. However, when the applied amount of water and fertilizer exceeded the

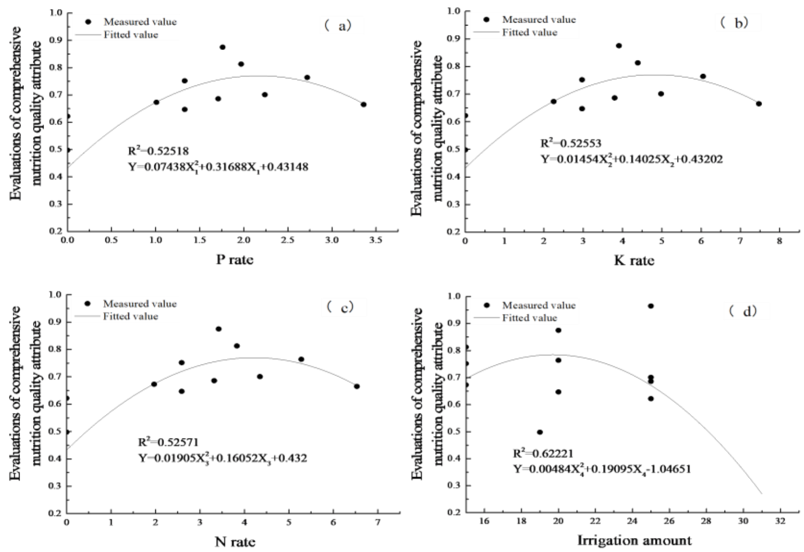

Fig. 3: Relationship between comprehensive nutritional quality and water and fertilizer factors of tomato

optimum value, trace elements of N, P and K as well as irrigation water amount would inhibit tomato comprehensive nutrition quality and further influenced it.

Influence of Multi-factors on Tomato Comprehensive Nutrition Quality

The correlation coefficient between single water and fertilizer factor and tomato comprehensive nutrition quality only, demonstrated the changing law with other factors of intermediate values. During the application process of water and fertilizer, the influence of multi-factors on tomato comprehensive nutrition quality could not be demonstrated due to the interaction of physicochemical properties. With independent variables of four factors including applied amount of P (x_1), K (x_2), N (x_3) and irrigation water amount (x_4) treated by different water and fertilizer as well as dependent variable of tomato comprehensive nutrition quality (Y), the regression equation as given below was obtained by multi-factor regression analysis of S.P.S.S. software.

$$Y = 1.094 + 114.326 X_1 + 86.442 X_2 - 157.77 X_3 - 0.026 X_4 + 13.322 X_1 X_2 - 7.791 X_1 X_4 + 6.686 X_2 X_3 - 5.346 X_2 X_4 + 10.137 X_3 X_4 \quad (4)$$

From significance test of regression equation (4), results showed that $F=1.60>F_{0.05}(9,2)=0.94$, illustrating that it was appropriate to adopt the specific model. Determination coefficients R^2 of 0.878 illustrated that four factors (x_1-x_4) dominated the change of tomato comprehensive nutrition quality. From the calculated T test value, the main effect of different single factor on tomato comprehensive nutrition quality was in a descending order of irrigation water amount (t=1.375)>N rate (t=0.636)>P rate (t=0.527)>K rate (t=0.383). It illustrated that it was necessary to pay attention to the coupling effect of water and fertilizer factor to guarantee the improvement of crop quality. Besides, appropriate ratio and applied amounts should be adopted. Tomato comprehensive nutrition quality was relatively larger with respective applied amounts of N, P and K and irrigation amount as 2.24, 6.06 and 5.78 g and 25 L, respectively. In this trial, T2 treatment (0.8AE_p, 20%BS) was regarded as the optimal.

Discussion

The establishment of tomato comprehensive nutrition quality evaluation index could effectively provide scientific basis for evaluation of tomato quality. Further, by coordinating the relationship between irrigation water and fertilizer application, scientific evidence for cycling the nutrients of biogas slurry through ecologically sound agricultural management system has been established (Du *et al*., 2019). Combined weights of different tomato single nutrition qualities obtained, were from not only the AHP method but also the variation coefficient method. Wherein, weight of health quality was higher than flavor quality. Further, weights of soluble protein and vitamin C were relatively higher and weights of titrate acid was relatively lower. On the one hand, soluble protein had effects of strong anti-oxidative activities (Liu *et al*., 2006; Drazkiewicz *et al*., 2010), assisted lowering of blood pressure (Lin *et al*., 2006) and enhancement of body immune regulation (Liu *et al*., 2007). Thus, the subjective weight in the AHP method was relatively higher. In the meantime, weight of flavor quality was lower than health quality by 0.046. The corresponding assigned weight index was relatively lower due to the relatively more number of indexes which was four. On the other hand, in this research, the influence of different water and fertilizer treatments on tomato vitamin C was relatively large. Besides, the corresponding influence on the sugar acid ratio was the smallest. It has been reported that there was significant influence of water and fertilizer treatment on vitamin C (Hernández *et al*., 2011). Thus, the establishment of assembly model of game theory could, not only decrease the subjective presumption of the AHP method but also combine the objective determined value organically, thus facilitating the research of tomato comprehensive nutrition quality.

There were many factors which influenced quality of vegetables and crops, among which genetic characteristic had the main function. Besides, water and fertilizer in the late phase also had significant influence on vegetable quality (Liu *et al*., 2011). When the type of the crop was same with the growth environment, the rational regulation of water and fertilizer would be critical for vegetable nutritional quality. Current research about the influence of crop quality, mainly focused on the relationship between water regulation and crop growth, yield as well as the quality but neglected the synergistic regulation effects of nutrients and water (Nangare *et al*., 2016; Yang *et al*., 2017; Ju *et al*., 2018; Elena *et al*., 2019). Biogas slurry is the good source of plant nutrients. The replacement of biogas slurry with fertilizer would not only establish the utilization of biogas slurry resources but also decreases the amount of chemical fertilizer to be used. Wu *et al*. (2013) showed that the application of biogas slurry would effectively enhance not only yield but also quality of rape seed. Domenico *et al*. (2019) showed that biogas slurry used as nutritional solution enhanced soluble sugar and soluble protein contents of lettuce. Present study showed that different treatments with water and biogas slurry had significant influence on tomato nutrition quality. Whereby, irrigation amount was the factor for it. However, when irrigation water amount exceeded the optimal value, it became the main limiting factor to effect tomato nutrition quality. Among other nutritional factors, N rate had the largest influence on tomato nutrition quality. The effect of nutrients like P and K on tomato nutrition quality followed a descending order *i.e*., P rate> K rate. Since biogas slurry contains >90% water, its application decreased the irrigation water amount which achieved the purpose of water resources saving. There were plenty of proteins, amino acids, sugar, humic acid, vitamin, some hormones and some pest and disease inhibiting active ingredients present in the tomato crop which had a good promotion function for the improvement of crop quality (Li *et al*., 2012).

This study adopted integrated irrigation of water and biogas slurry which belonged to the scope of water-fertilizer integration technology. Whereas, it had been proved to effectively enhance the water fertilizer utilization efficiency of crop, which thus improved the crop quality (Li *et al*., 2017). In present study, the relative closeness degree A_i^* of T2 ($0.8AE_p$, 20%BS) treatment was the highest in the evaluation of tomato comprehensive nutrition quality. This illustrates that the treatment could satisfy the formation of tomato nutrition quality on supply of water and nutrients. This function further verified that the integration of water and biogas slurry would generate positive effect on the formation of tomato nutrition quality.

Conclusion

On the basis of weights of different tomato single nutrition quality could be determined which followed a descending order of action *e.g*., C>soluble protein>the sugar acid ratio>soluble sugar>soluble solids>titrate acid. The order of tomato comprehensive nutritional quality evaluation values A_i^* determined by TOPSIS method was positively correlated with the determined values of different tomato single nutrition qualities. Thus, tomato comprehensive nutrition quality has therefore been accurately evaluated.

The response extent of tomato comprehensive nutrition quality to different water and fertilizer factors was different and followed a descending order: irrigation water amount>N rate >P rate >K rate. When other factors were at intermediate level, the variation relationship between tomato comprehensive nutrition quality and P, N and K rates and irrigation water amount all fitted in quadratic curves. During the growth period of crops, to guarantee the enhancement of the crop quality, it was necessary to pay attention to the coupling effect between water and fertilizer factors in order to adopt reasonable ratio and application amount. When P, K and N rates and irrigation water amount were 2.24, 6.05, 5.78 g and 25 L, respectively, tomato comprehensive nutritional quality reached a larger value and T2 ($0.8AE_p$, 20%BS) treatment was considered as the optimum.

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