EFFECTS OF BIOGAS SLURRY IRRIGATION ON TOMATO (*SOLANUM LYCOPERSICUM* L.) PHYSIOLOGICAL AND ECOLOGICAL INDEXES, YIELD AND QUALITY AS WELL AS SOIL ENVIRONMENT

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Abstract. Replacement feasibility of inorganic fertilizer using biogas slurry was investigated via two-season pot culture experiments in greenhouse. Three biogas slurry treatments (treatment 1, T1; treatment 2, T2; treatment 3, T3) and a inorganic fertilizer treatment (CK) were set to explore the effects on tomato growth, yield, quality and root-zone soil environment. The volume concentrations of biogas slurry in T1, T2 and T3 treatments were 20, 15 and 10%, respectively. Results showed that T1 and CK treatments maintained a high leaf area index (LAI), photosynthetic rate and chlorophyll (a+b) contents during the whole growing period. T1 treatment can obtain an equivalent yield to CK, however, the yield of T2 and T3 treatments were inferior to that of CK. For the quality of tomato, T1 treatment can improve the soluble sugar and titratable acid contents for about 19.07 and 4.17% when compared to CK, and T2 treatment can improved about 7.55 and 4.17%. Furthermore, T1 and T2 treatment can get a better sugar-acid ratio and tastes. In comparison with inorganic fertilizer treatment, all biogas treatments could increase soil porosity and soil aggregate, decrease soil debris, in which the superior treatment is T1 and can be considered as a good organic fertilizer.
Keywords: *leaf area index, photosynthetic rate, chlorophyll, comprehensive benefit evaluation, soil saturated hydraulic conductivity, soil organic matter, soil total nitrogen, soil microstructures*

Introduction

Application of inorganic fertilizers has played a significant role in the development of food and other agricultural crop productions (Smith et al., 2015). However, recent researches showed that the production benefit did not increase proportionately with the quantity of fertilizer input (Liu et al., 2017). Application of fertilizer in excess, not only increased the cost of agricultural products, but also result environmental problems such as soil hardness and soil acidification of the cultivated lands. A reduction in the amount of applied fertilizer could bring the cost of agricultural production down, enhance efficiency, save energy and reduce emissions. As a result the national food security, agricultural product quality and agricultural ecological condition all become saved (Li et al., 2016). It has been verified that organic fertilizers could promote the healthy growth of crops and enhance yield and quality of crops through improving soil structure of fungal community (Ding et al., 2017; Rong et al., 2018). Thus, the replacement of inorganic fertilizer with the organic ones could bring a safer food production system with adequate achievements of ecological and environmental safety of the cultivated lands.

Biogas slurry is the post-product of biogas production technology via anaerobic fermentation process. It is an effective organic fertilizer, which contains the most basic water soluble nutrients necessary for crop growth, such as N, P and K. Besides, it also contains microelements like Ca and Mg and some essential amino acids as well as growth stimulating and regulating materials including vitamins and growth hormones. Application of biogas slurry irrigation could enhance crop yield, optimize fruit quality, promote crop seed germination, prevent diseases and pests, and improve soil quality (Tambone et al., 2010; Ledda et al., 2013; Oh et al., 2014). Duan et al. (2011) applied biogas slurry as liquid fertilizer on greenhouse cucumber production. They obtained high yield and good quality of cucumber compared with inorganic fertilizer treatment. Their experiment had also achieved a reduction of greenhouse gas emission. Alburquerque et al. (2012) showed that the application of biogas slurry could effectively improve soil environment and obtain yield which was comparable with that obtained by traditional fertilizer application. Using biogas slurry in the field increased the population of microorganisms which contributed to the formation of soil organics (Coban et al., 2015). Nabel et al. (2017) carried out a comparative experiment of three years duration and showed that the application of biogas slurry as fertilizer could enhance carbon content, water holding capacity and fertility of soils. Lu et al. (2012) showed that irrigation by appropriate biogas slurry could enhance rice yield compared with traditional fertilizer use. Besides, the heavy metal concentration of underground water, soil and rice, determined after one week of biogas slurry irrigation were seen unaffected. Actually biogas slurry contains high water content and low fertilizer properties. However, in current researches, biogas slurry was treated simply as fertilizer and applied each time according to the calculated equivalent fertilizer application amounts. This had resulted in the loss of nutrient and a decrease of nutrient utilization efficiency. In addition, current researches did not consider comprehensively the effect of biogas slurry on crop growth elements, yield and quality, soil nutrient and micro-aggregation structure of roots over the whole growth period. Besides, there was a lack of study on the effect of application of biogas slurry as replacement of inorganic fertilizer. Considering the above mentioned knowledge gaps, it has been aimed in the present research to study the effect of application of biogas slurry in different concentrations on tomato cultivation. In the present research, physiological and ecological indexes, yield and quality, as well as the soil environment of root of tomato plant were considered to study over the entire growth period. Another objective of this research was to evaluate the tomato comprehensive benefit using the ‘Technique for order preference by similarity to ideal solution’ (TOPSIS). This would enable to obtain appropriate biogas slurry irrigation mode during the whole tomato growth period in realization of providing theoretical support for further field application as total replacement of inorganic fertilizer.

Materials and Methods

Experimental materials

In the present research, pot culture experiments were performed in the spring and autumn seasons of 2017. The experimental site was the greenhouse of the demonstration

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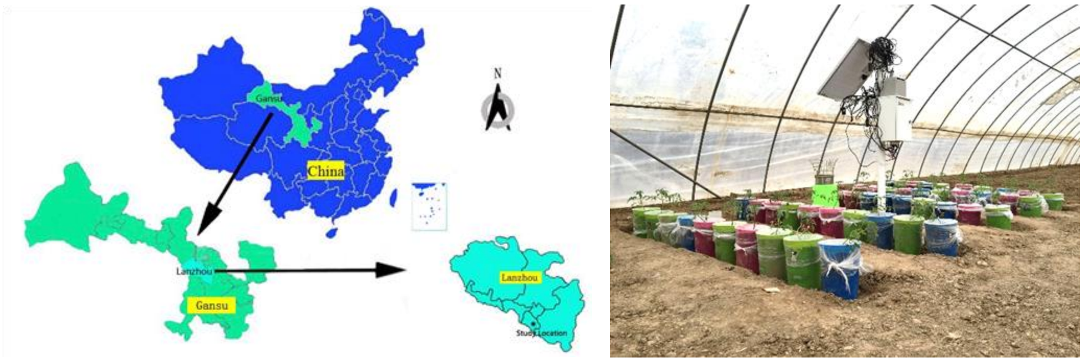
site of integration of facilities, vegetables, water and fertilizer at Weiling Country, Qilihe District, Lanzhou City, Gansu Province of the People’s Republic of China. The experimental criteria were: Daylight greenhouse with the type of ridge 50.0 × 10.5 ×4.0 m (L×W×H) at 36º03’ N and 103º40’ E and with an average altitude of 1872 m (*Figure 1*). The study area is subjected to a temperate continental dry climate with sufficient sunlight and little rain. Average annual temperature was 8.9ºC with a no-frost period of about 150 d. Average annual precipitation and evaporation were 310.5 and 1158.0 mm, respectively. There was a minimized automatic weather site in greenhouse to constantly monitor conventional meteorological data.



(a) (b)

Figure 1. *Research site location and pot culture experiment equipment in greenhouse. (a) The research site location; (b) the pot culture experiment equipment*

Tomato (*Solanum lycopersicum* L.) cultivar “No.3 of Hongbao” was tested in pot culture experiments. The soil used in this experiment was collected from the indoor surface layer of 0-40 cm within the greenhouse complex. Soil particle size distribution was determined by laser particle size analyzer (MS2000). The calculated ratios of sand, silt and clay to total weight were 25.3, 64.6 and 10.1%, respectively. According to International soil texture classification standard, the tested soil was silt. Soil nutrient condition was determined before potting. Contents of total N, organic matter, and total P were 1.022, 9.08 and 1.616 g/kg, respectively. The bottom and top diameter of the cultivation container, the height of soil and the unit weight of soil were 16, 22 and 22 cm and 1.35 g/cm^3, respectively. Field water holding content, namely, weight water fraction θ_f was 23.5%. A hole at the bottom of pot was drilled for ventilation. Gauze and filter paper were put at the bottom to prevent the leakage of soil. To monitor soil water fraction a hole was drilled at the wall of the pot. Tomato was permanently planted with a seedling of four big leaves and one heart. The growth period of tomato in the experiments was shown in *Table 1*. In the experiment 1500 ml slow seedling water in permanent planting was unifiedly irrigated. The plastic film was covered 5 d after permanent planting. Soil evaporation could be neglected. Other cropping management practices, such as pesticide and herbicide application, were consistent with those used by local farmers.

The tested biogas slurry was collected from the biogas tank with normal fermentation and normal gas production in Gansu Hesitan cows breeding center in Huazhuang Country, Lanzhou City. After two months of aeration and standing, the clear liquid was extracted for further use until the physicochemical properties stabilized. The biogas engineering perennially used cow dung as fermentation material. Nutritional status of the

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biogas slurry were 10.75, 1.036, 0.533 and 1.186 g/L for organic matter, total N, P and K contents, respectively.

Table 1. *The growth period of tomato in the experiments*

Planting time	Growth period	Date	Days	Planting time	Growth period	Date	Days
Plant in spring	Seedling stage	12-28th May	16	Plant in autumn	Seedling stage	14-29th September	16
	Flowering stage	May 29th to June 9th	12		Flowering stage	September 30th to October 9th	10
	Fruit swelling stage	June 10th to July 3rd	24		Fruit swelling stage	October 10th to November 10th	31
	Fruit maturity stage	4-21st July	18		Fruit maturity stage	11-29th November	19

Experimental design

In the experimental trials, hole irrigation water-biogas slurry integration method was applied (Tan et al., 2015). Four treatments were set, wherein CK was the routine fertilizer treatment and T1, T2 and T3 were the biogas slurry treatments with volume concentrations of 20, 15 and 10%, respectively. Inorganic fertilizer application of CK treatment in tomato growth period was as follows: once in each of the seedling and flowering stage and twice in each of the fruit swelling stage and fruit maturity stage with urea, P and K fertilizer. The application amounts for NPK were 78, 94.5 and 97.5 kg/ha, respectively.

During the entire growth period, the biogas slurry treatment adopted integration irrigation of water and biogas slurry. Namely, irrigation was conducted with biogas slurry of different concentrations. The irrigation amount was calculated by the evaporation amount of the standard evaporating dish of Φ20 cm which was put at the height with a distance of 20 cm to tomato canopy. The evaporation amount of cumulative 2 d was set as the irrigation standard. The irrigation frequency was 1 time/2 d.

The calculation method was according to (*Eq.1*) (Azizi-Zohan et al., 2008)

$$M = K_p \times S \times E_p \tag{Eq.1}$$

where, M was the irrigation water amount in mL; Kp was the crop-pan coefficient; S was the irrigation water amount control area with the unit of cm^2; Ep was the evaporation amount of the evaporating dish in the gap between two irrigation with the unit of mm.

To illustrate the difference between the integration irrigation of water and biogas slurry and traditional fertilizer treatment in tomato whole growth period as well as to obtain appropriate biogas slurry concentration, none of water deficit treatment was set in different growth periods of crop in experiment.

Thus, Kp value was set as 1.0 in the experiment. In addition, three replicates were set for each treatment.

The determination of indexes and methods

The determination of physiological and ecological indexes

Leaf area index (LAI) was determined by the image method using Photoshop software. Three plants in each treatment were chosen to measure and the final LAI are the average

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value. In the seedling and flowering stages, the LAI for each treatment was measured once. However, in the fruit swelling and maturity stages this parameter was measured twice for the longer period of these two growth stages. The measurement of LAI followed the scanning of the leaf first with the help of a scanner and then the leaf area was calculated with the software of Photoshop. Finally, the value of LAI was obtained according to the equation (Eq.2):

$$\mathrm{LAI} = A_l / A_s \qquad \text{(Eq.2)}$$

where, A_l is the total leaf area of a single plant, A_s is the irrigation water amount control area of a plant.

Soil water fraction was determined by WET three parameter calibrated tester. The determination was done at 2 days during the growth period. Chlorophyll was determined by the mixed solution method of acetate and ethanol (Liu et al., 2018) before and the third day after the first fertilizer application as well as before the second fertilizer application in the fruit swelling stage. The photosynthetic rate was determined by CIRAS-I portable photosynthesizer (made in UK) during 9:30 to 10:30 AM of sunny day in different tomato growth periods. The photosynthetic rate was determined on May 22 and September 21 in seedling stage, and measured on June 2 and October 6 in flowering stage, on June 24 and October 19 in the fruit swelling stage and on July 15 and November 20, 2017 for tomato planted in spring and autumn. Weights of dry materials were determined by the drying method. Samples were collected at the end of different tomato growth periods. For each treatment, three crops were determined separately, whose average value was reported as experimental final result.

Quality index determination

Soluble solids of tomato fruit contents were determined by WAY-2S Abbe refractometer. Vitamin C, soluble protein, total soluble sugar and the titrate acidity were determined by Molybdenum blue colorimetry, Coomassie brilliant blue G-250 staining method, Anthrone colorimetry method and the titration method (Liu et al., 2018), respectively.

Soil environment index determination

Soil saturated hydraulic conductivities were determined by the variable water level method with soil sampling by cutting ring after experiment. Total N content in soil was determined by Kjeldahl method. Soil microstructure was determined by imaging via scanning electron microscope (SEM), whose figure was treated by Photoshop CS6 software.

Data processing and analysis

Each data was the average of three replicate determinations. Turkey HSD of the variance analysis and the significance of difference were conducted by SPSS 19.0 statistical analysis software. Figures were drawn by Excel 2010 and Origin 8.0. Tomato comprehensive benefit was evaluated by TOPSIS analysis method.

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Results and analysis

The response pattern of tomato physiological and ecological indexes on different treatments

LAI

Figure 2 showed the changing pattern of LAI of different treatments over the whole growth period. It showed that LAI of tomato which was planted in spring was significantly larger than that of autumn treatment. LAIs of different biogas slurry treatments in two growth periods were in a descending order of T1>T2>T3, whereas LAI of CK treatments in stages of seedling, blossoming and fruiting, and pre fruit swelling stage of tomato was the maximum among all, namely CK>T1>T2>T3, respectively. However, LAI of CK treatment in the late fruit swelling stage gradually decreased to be lower than that of T1 treatment. The pattern followed T1>CK>T2>T3. Besides, LAI in the late fruit maturity stage decreased dramatically. The changing trend of LAI illustrated that the fertilizer application in tomato nutritional growth period could provide optimum nutrient supply for tomato, whereas during the gradual transition of tomato from nutritional growth to reproductive growth, CK treatment on the aspect of sustainable support of crop growth was insufficient. In addition, LAI of T1 treatment demonstrated a much higher level in the entire tomato growth period, especially in the fruit swelling stage. During which period the value was far higher than those of other treatments. Thus, it demonstrated better growth persistence and illustrated that the water and fertilizer supply of T1 treatment could obtain better LAIs with the corresponding biogas slurry concentration and irrigation frequency.

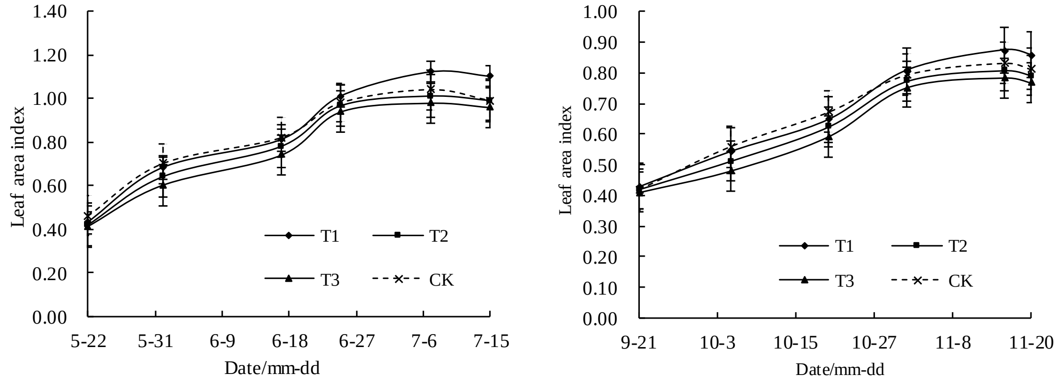

Figure 2. *Growth stage variations of tomato leaf area index under different treatments. The error bars mean a 5% range of error. CK is the control treatment applied with inorganic fertilizer, T1, T2 and T3 are treatments applied with biogas slurry of 20, 15 and 10% in volume concentrations, respectively*

The photosynthetic rate

From *Table 2*, leaf photosynthetic rates of CK treatment in tomato seedling as well as flowering stages in both spring and fall experiments were significantly higher than those of biogas slurry treatments (T1, T2 and T3) and with apparent advantages. Leaf photosynthetic rates of T1 treatment in fruit swelling and maturity stages were apparently higher than those of other treatments. It followed a descending order of T1>CK>T2>T3.

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The leaf photosynthetic rates of T1 treatment were 0.06 and 0.07 μmol/m^2/s as well as 0.10 and 0.09 μmol/m^2/s higher than those of CK treatment in spring and fall cultivation, respectively.

Table 2. *Leaf photosynthetic rate of tomato in different growth stages*

Treatments	Planted in spring				Planted in autumn			
	Seeding stage (μmol m^{-2}s^{-1})	Flowering stage (μmol m^{-2}s^{-1})	Fruit swelling stage (μmol m^{-2}s^{-1})	Fruit maturity stage (μmol m^{-2}s^{-1})	Seeding stage (μmol m^{-2}s^{-1})	Flowering stage (μmol m^{-2}s^{-1})	Fruit swelling stage (μmol m^{-2}s^{-1})	Fruit maturity stage (μmol m^{-2}s^{-1})
CK	7.96aA	8.26aA	8.06abAB	8.12bA	8.16aA	7.86aA	7.46bB	6.76bB
T1	7.84bB	8.16bB	8.12aA	8.19aA	8.10bA	7.82aAB	7.56aA	6.85aA
T2	7.82bB	8.06cC	8.00bB	7.98cB	8.08bA	7.76bBC	7.42cC	6.66cC
T3	7.80bB	8.00cC	7.86cC	7.82dC	8.06bA	7.72bC	7.34dD	6.46dD

Lowercase a, b, c, d indicate significantly differences among treatments at the level of P<0.05; Capital letters A, B, C, D indicate significantly differences among treatments at the level of P<0.01. CK is the control treatment applied with inorganic fertilizer, T1, T2 and T3 are treatments applied with biogas slurry of 20, 15 and 10% in volume concentrations, respectively

In the two seasonal experiments namely, spring and autumn, leaf photosynthetic rates of T1, T2 and T3 treatments were 0.8 and 1.3%, 2.1 and 2.4%, as well as 4 and 4.5% higher than those of CK treatment, respectively. In tomato seedling stage, there was no significant variation among different biogas slurry treatments (T1, T2 and T3), e.g. the largest variance was only 0.5%. In the flowering stage of spring cultivation, there was significant difference between tomato leaf photosynthetic rate of T1 treatment and those of T2 and T3 treatments. But there were no significant difference between T2 and T3 treatment In addition, rate of T1 treatment was 1.2 and 2.0% higher than those of T2 and T3 treatments, respectively. However, in the flowering stage of fall cultivation, rate of T1 treatment was 0.8 and 1.3% higher than those of T2 and T3 treatments, respectively. This means that there started a certain degree of differentiation between the nutrient supply of biogas slurry and the tomato growth demand at the time of gradual transition from tomato nutritional growth to reproductive growth. This also affected the leaf photosynthesis to some extent. In the stages of fruit swelling and fruit maturity, the photosynthetic rate of T1 treatment was significantly higher than those of T2 and T3 treatments. This indicates that T1 treatment could better promote leaf photosynthetic rate of tomato during tomato reproductive growth stages which promotes further the synthesis of photosynthetic products.

Chlorophyll

Chlorophyll in leaves could demonstrate the photosynthetic ability of leaf to some extent. *Figure 3* showed the variation of chlorophyll (a+b) content with different treatments. Chlorophyll (a+b) content of CK treatment before the first fertilizer application in the fruit swelling stage was 0.055 and 0.025 mg g/FW which was lower than that of T1 treatment in two seasonal experiments, respectively (*Figure 2*).

Leaf chlorophyll (a+b) contents at the 3rd-5th day after the fertilizer application which were 0.067 and 0.048 mg g/FW higher compared to the values before fertilzer application, respectively. The values were the highest among those of different treatments, namely, 0.045 and 0.028 mg g/FW higher than those of T1 treatment.

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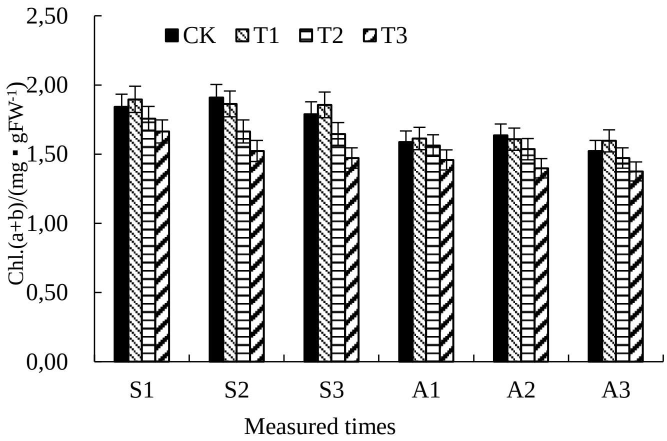

Figure 3. *Chlorophyll (a+b) content in tomato leaves under different treatments. S1, S2 and S3 were the chlorophyll (a+b) in spring experiment, and A1, A2 and A3 were that in autumn experiment of 2017. CK is the control treatment applied with inorganic fertilizer, T1, T2 and T3 are treatments applied with biogas slurry of 20, 15 and 10% in volume concentrations, respectively. The error bars mean a 5% range of error. Chl., chlorophyll; FW, fresh weight*

Leaf chlorophyll (a+b) content of CK treatment before the second fertilizer application in the fruit swelling stage decreased 0.119 and 0.113 mg g/FW compared with those of T1 treatment, respectively. Leaf chlorophyll (a+b) content of T2 and T3 treatments were lower than those of CK and T1 treatments and demonstrated a decreasing trend. The overall change of leaf chlorophyll (a+b) content of T1 treatment was the most stable among those of different treatments with respective changing amplitudes of only 0.04 and 0.017 mg g/FW of two seasonal experiments.

Besides, the changing amplitude of T3 treatment in two seasonal experiments was the largest i.e., 0.119 and 0.113 mg g/FW, respectively. The next largest changing amplitude was 0.111 and 0.09 mg g/FW of CK treatment. Thus, it showed that T1 treatment could maintain leaf chlorophyll (a+b) content at a stable level.

The response trend of tomato yield and quality

From *Table 3*, in 2017 spring experiment, the yield of T1 treatment was highest. The next was that of CK treatment. The yield of T1 treatment was 11.8 and 31.7% higher than those of T2 and T3 treatments, respectively. There was a significant difference between CK and T1 treatment at the level of p=0.05.

However, in 2017 autumn experiment, the yield of CK treatment was the highest. The next was that of T1 treatment. The yield of CK treatment was 15.5 and 18.2% higher than those of T2 and T3 treatments, respectively. However, there was no significant difference between the yield of CK treatment and that of T1 treatment at levels of p=0.05 and p=0.01.It illustrated that T1 treatment could not only replace fertilizer but also obtain the yield which was comparable with that of traditional fertilizer treatment. Different nutritional qualities of T1 and T2 treatments in two season experiments were higher than those of CK treatment, wherein total soluble sugar and titrate acid contents of T1 treatment were 19.07 and 16.30% as well as 4.17 and 10.32% higher than those of CK treatment, respectively.

Besides, total soluble sugar and titrate acid contents of T2 treatment were 75.5 and 7.70% as well as 2.24 and 7.54% higher than those of CK treatment, respectively.

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Table 3. *Effects of different treatments on tomato yield and nutritional quality*

Planting time	Treatments	Yield/(g)	Nutritional quality				
			Titration acid/(%)	Total sugar/(%)	Sugar/Acid	Vitamin C /(mg•100g^{-1})	Soluble protein/(mg•g^{-1})
Planted in spring	CK	321bA	0.312abA	3.178cC	10.186cC	20.834cC	1.078cC
	T1	332aA	0.325aA	3.784aA	11.643aA	23.465aA	1.132aA
	T2	287cB	0.319abA	3.418bB	10.715bB	22.722bB	1.105bB
	T3	252dC	0.286bB	2.859dD	9.997dD	20.011dD	0.986dD
Planted in autumn	CK	268aA	0.252cB	2.626cC	10.421bB	18.847cC	0.912bB
	T1	259aA	0.278aA	3.054aA	10.986aA	19.973aA	0.967aA
	T2	232bB	0.271bA	2.828bB	10.435bB	19.077bB	0.923bB
	T3	219cB	0.244dB	2.311dD	9.471cC	18.376dD	0.881cC

Lowercase a, b, c, d indicate significantly differences among treatments at the level of $P<0.05$; Capital letters A, B, C, D indicate significantly differences among treatments at the level of $P<0.01$. CK is the control treatment applied with inorganic fertilizer, T1, T2 and T3 are treatments applied with biogas slurry of 20, 15 and 10% in volume concentrations, respectively

In addition, the sugar acid ratio of T1 treatment was 14.3, 8.6 and 16.5% higher than those of CK, T2 and T3 treatments, respectively in spring cultivation as well as 5.4, 5.2 and 16.0% higher in autumn cultivation, respectively. Besides, the sugar acid ratio of T2 treatment was 5.19 and 0.13% higher than those of CK treatment in spring and fall, respectively.

Vc contents of T1 and T2 treatment were 12.58 and 5.97% higher than those of CK treatment in spring cultivation as well as 9.02 and 1.02% higher in fall cultivation, respectively. Different nutritional quality indexes of T3 treatment was the lowest among those of different treatments.

Results showed that T1 and T2 treatments not only obtained a higher soluble sugar content and the titrate acidity but also increased the sugar acid ratio, Vc, and soluble protein contents. All these factors contributed to increase the nutritional value as well as the taste and flavor of tomato. However, T3 treatment was unfavourable to the formation of tomato nutritional quality, illustrating the effect of biogas slurry irrigation frequency and concentration on tomato yield and quality to some extent. Thus, the appropriate biogas slurry irrigation mode could effectively improve the nutritional quality of tomato.

Tomato comprehensive benefit evaluation by the TOPSIS method

To obtain the optimum biogas slurry irrigation mode over the whole growth period of tomato, seven indexes such as yield, soluble solids, the soluble sugar, the titrate acid, the sugar acid ratio, the soluble protein and vitamin C were chosen. Besides, as shown in *Table 4*, tomato comprehensive benefit was evaluated by the TOPSIS method. Thus, in 2017 spring and fall experiments, comprehensive benefit indexes (CIs) of different treatments as well as comprehensive sorting were in a descending order of T1>T2>CK>T3. In addition, CI value of T1 treatment was 31.21 and 40.86% higher than those of CK treatment, respectively. This illustrated that T1 treatment was better than traditional fertilizer treatment. So, on the comprehensive benefit aspects of tomato yield and nutritional quality, T1 could be recommended as reference mode for the replacement of fertilizer with biogas slurry.

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Table 4. *Tomato comprehensive benefit evaluated by TOPSIS*

Planting time	Treatments	Yield	Titration acid	Total sugar	Sugar/Acid	Vitamin C	Soluble protein	D^{+}	D^{-}	CI	Rank
Planted in spring	CK	0.5356	0.5018	0.4776	0.4780	0.5207	0.5006	0.1367	0.3039	0.6897	3
	T1	0.5540	0.5227	0.5687	0.5464	0.5864	0.5257	0.0000	0.4058	1.0000	1
	T2	0.4789	0.5131	0.5137	0.5028	0.5678	0.5132	0.1056	0.3441	0.7651	2
	T3	0.4205	0.4600	0.4297	0.4691	0.2502	0.4579	0.4058	0.0000	0.0000	4
	A^{+}	0.5540	0.5227	0.5687	0.5464	0.5864	0.5257				
	A^{-}	0.4205	0.4600	0.4297	0.4691	0.2502	0.4579				
Planted in autumn	CK	0.5463	0.4816	0.4830	0.5038	0.4900	0.4950	0.1073	0.1265	0.5411	3
	T1	0.5279	0.5313	0.5617	0.5311	0.5248	0.5248	0.0183	0.1971	0.9149	1
	T2	0.4729	0.5179	0.5201	0.5045	0.5013	0.5009	0.0955	0.1242	0.5653	2
	T3	0.4464	0.4663	0.4250	0.4579	0.4829	0.4781	0.2054	0.0000	0.0000	4
	A^{+}	0.5463	0.5313	0.5617	0.5311	0.5248	0.5248				
	A^{-}	0.4464	0.4663	0.4250	0.4579	0.4829	0.4781				

D^{+} and D^{-} mean the weighted distances between each alternative and the optimal or inferior ideal solutions, respectively; A^{+} and A^{-} are the optimal and inferior ideal solutions, respectively. CK is the control treatment applied with inorganic fertilizer, T1, T2 and T3 are treatments applied with biogas slurry of 20, 15 and 10% in volume concentrations, respectively

The effect of different treatments on soil environment

Soil saturated hydraulic conductivity and soil organic matter

By studying the trend of soil saturated hydraulic conductivities of different treatments, it has been seen that T1 was apparently higher than other treatments (*Figure 4*). Soil saturated hydraulic conductivities (Ks) of different treatments was in a descending order of T1>T2>CK>T3. In the two experiments carried out in both the seasons, the values of T2 treatment were 0.002 and 0.005 cm/min higher than those of CK treatment, respectively. Besides, values of T3 treatment were the lowest, illustrating that T1 and T2 treatment could provide higher soil saturated hydraulic conductivities than CK treatment.

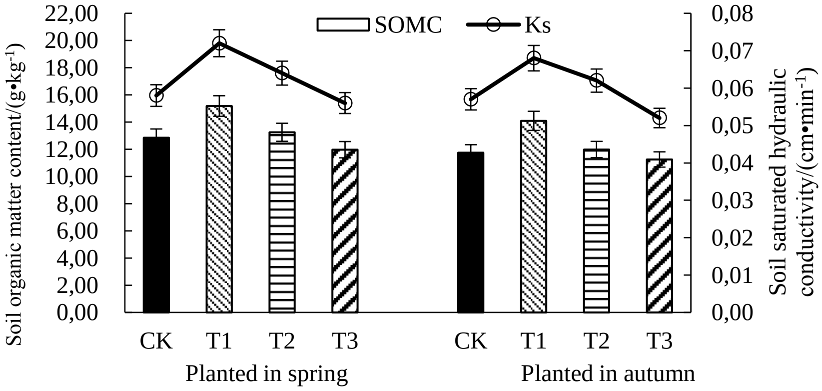

Figure 4. *Soil organic matter and saturation conductivity under different treatments. CK is the control treatment applied with inorganic fertilizer, T1, T2 and T3 are treatments applied with biogas slurry of 20, 15 and 10% in volume concentrations, respectively. The error bars mean a 5% range of error*

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In 2017 spring and autumn experiments, soil organic matter content (SOMC) of all treatments increased compared with the original soil as shown in dashed line of *Figure 4*. Besides, values of CK treatment which were 22.80 and 18.39% higher than those of original soil, respectively, were lower than those of T1 and T2 biogas slurry treatments.

SOMC of different treatments related in a descending order T1>T2>CK>T3. Its content in T1 and T2 treatments were 18.13 and 19.91%, respectively which were 10.34 and 8.77% higher than CK treatment. However, the contents were 3.57 and 3.63% higher than those of T3 treatment, respectively, in spring and fall experiments. All these illustrated that T1 and T2 treatment were better than CK treatment on the aspect of increasing SOMC. Therefore, the finding supports that appropriate biogas slurry irrigation could increase SOMC.

Change of soil total N content

From *Table 4*, soil total N content of CK treatment was the highest in tomato different growth stages in spring and fall and the next was T1 treatment. On the other hand, the soil total N content was the lowest in T3 treatment. The soil total N contents of different treatments from the seedling to the flowering stages, increased to some extent. The increasing amplitudes of soil total N of T3 treatment were the smallest i.e., 0.007 and 0.002 g/kg, in spring and fall, respectively. This illustrates that N supply of different treatments from the seedling stage to the flowering stage was surplus. Thus, N fertilizer application amount or biogas slurry concentration could be proportionately decreased in the application process. T3 treatment could be used as reference for the application during the corresponding growth period. Considering soil N contents in stages of blossoming and fruiting, fruit swelling stage and fruit maturity stage, the change of T1 treatment was stable with the smallest changing amplitudes or increasing amounts of only 0.007 and 0.004 g/kg. On the other hand, the increased amounts of CK treatment were 0.117 and 0.216 g/kg, illustrating that N element provided by traditional fertilizer treatment has been accumulated to some extent in soil. However both the T2 and T3 treatments demonstrated the decreasing trend, especially T3 whose soil N content was already lower than that of original soil (1.022 g/kg) in stages of fruit swelling stage and fruit maturity stage. This clarifies that T3 treatment could not satisfy the N element demand of tomato growth. Values of T1 treatment were stable.

The influence of different treatments on soil microstructures

Soil microstructure reflects the original soil characteristics which is directly related to soil fertility and happens to be an important compositional part of soil quality (Kapur et al., 2007; Price et al., 2007). From *Figure 5*, soil of CK treatment was in debris aggregation state with the close contact between soil bone particles and soil matrix. Soil of T1 treatment was in the status of cementitious compactness with a microstructure distribution of flocculated mass as well as the loose contact of bone particles and soil matrix. Soil debris of T2 treatment was fewer than that of CK treatment with apparent better soil pore development than that of CK treatment.

There was a compacting contact between soil bone particles and soil matrix in T3 treatment as well as an apparent higher amount of soil debris than those of T1 and T2 treatments but lower amount than that of CK treatment. The pore area, average pore area and average pore size of T1 treatment, which were the highest among different treatments were 31.62, 55.39 and 14.51% higher than those of CK treatment, respectively (*Table 5*).

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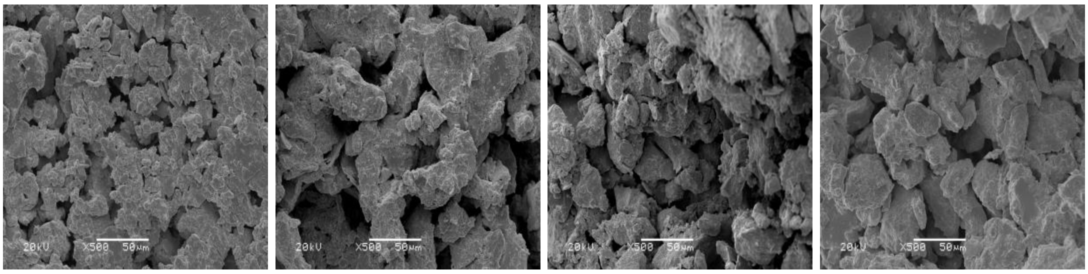

Figure 5. *Comparison of soil microstructure under different treatments (500 times). CK is the control treatment applied with inorganic fertilizer, T1, T2 and T3 are treatments applied with biogas slurry of 20, 15 and 10% in volume concentrations, respectively*

Table 5. *Pore parameters of different treatments after image treatment*

Treatments	The pore area (μm^2)	Average pore area (μm^2)	Average pore size (μm)	Area ratio
CK	4824.00c	19.93d	3.79b	0.071
T1	6349.21a	30.97a	4.34a	0.081
T2	5118.24b	21.24c	3.83b	0.073
T3	2859.68d	24.87b	3.70c	0.051

CK is the control treatment applied with inorganic fertilizer, T1, T2 and T3 are treatments applied with biogas slurry of 20, 15 and 10% in volume concentrations, respectively

It illustrated that the intensity of soil aggregation could be increased by biogas slurry application, leading the loose contact between bone particles and soil matrix which promoted the formation of different loose pores as well as the improvement of soil quality.

Discussions

LAI, photosynthetic rate as well as chlorophyll (a+b) were important indexes which demonstrated plant growth status and related to the sufficiency of N element supply to some extent (Inoue, 2003; Roca et al., 2018; Feng et al., 2018). In this work, LAIs of CK treatment in stages of seedling, blossoming and fruiting, and pre-fruit swelling stage were the highest. However, the value decreased gradually until a lower value than T1 treatment in the late fruit swelling stage is reached. The photosynthetic rate of CK treatment was the highest in stages of seedling as well as blossoming and fruiting.

T1 treatment was the best at key stages of the crop yield like fruit swelling stage and fruit maturity stage over the tomato reproductive periods. It also maintained stable chlorophyll (a+b) content of the crop. However, there was an apparent phase effect for current fertilizer application modes and methods. The promotion effect of which existed only for a short time period and after application decreased gradually with the increase of time. Thus it demonstrates a poor sustainability.

In the present experiment, biogas slurry concentration and irrigation frequency of T1 treatment could make tomato different physiological indexes over the growth period more stable compared with CK treatment. This indicates that a lot of inorganic N as well as many active materials which stimulated the growth of plants could be more easily absorbed by plants compared with inorganic fertilizer applications. Thus, it enhanced the nutrient absorption and utilization efficiency of crop plants (Wu et al., 2013; Rive et al.,

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2016). In all the treatments of the present experiment same irrigation methods were adopted. This verified that the integration technology and fertilizer application were appropriate. Water availability and nutrient absorption by crops with the same irrigation methods were optimum, wherein the reasonable nutrient concentration in the integration of water and fertilizer (Liang et al., 2013; Abalos et al., 2014; Al-Qurashi et al., 2015) could better promote the growth of crops.

The reasonable utilization of water and fertilizer was the key factor to enhance crop yield, quality and utilization efficiency of water and fertilizer (Hebbar et al., 2004). Al-Qurashi et al. (2015) showed that nutrient concentration was the key factor which influenced the crop yield. In this study, yield of T1 treatment was higher in spring and lower in fall than that of CK treatment. On the other hand, there was no significant difference between those two, illustrating that T1 treatment could satisfy the water and nutritional condition of tomato yield. Thus, T1 treatment could be an alternative for the replacement of traditional fertilizer use. However, crop quality determined market competitiveness. With the improvement of people’s living standard, crop fruit quality has been paid more and more attention (Luo and Li, 2018). Nutritional quality of vegetables usually depends upon their genetic characteristics and environmental factors such as irrigation, soil and fertility. Yue et al. (2003) proposed that whether or not, tomato was delicious and tasty, that depends on the soluble sugar content as well as absolute content of the titrate acid. In this study, soluble sugar content and absolute content of the titrate acid of T1 and T2 treatment were higher than those of CK. Whereas, those of T3 treatment were the lowest, illustrating that appropriate biogas slurry concentration could effectively improve nutritional quality of tomato. After analysis, various organic and inorganic salts, microelements and soluble materials of many amino acids, hydrolase, etc. were found to be present in biogas slurry (Wu et al., 2013). These were generated via fermentation process, wherein the microelements not only involved directly in many physiological metabolic processes of plant but also were the basis of dry material accumulation (Xing et al., 2014). Besides, those active materials of amino acids and hydrolase had important regulatory functions of crop growth and development. Thus, application of reasonable concentration of biogas slurry as well as the utilization water-biogas slurry integration provided better conditions for the formation of crop yield as well as the quality enhancement.

Soil saturated hydraulic conductivity was not only an important factor for the calculation of soil water movement but also a comprehensive ratio coefficient which described the permeability of porous media (Liang et al., 2009). In addition, organic matter was the main driving factor of increasing soil saturated hydraulic conductivity (Peng et al., 2010).

Results from the present study showed that every treatment could increase not only soil saturated hydraulic conductivity but also soil organic matter content. Current research showed that organic matter could absorb more cations and make soil nutrient preserving capability and the buffering capacity high. Parallel to this it could also loosen the soil, contributing to the formation of soil structure (Nabel et al., 2017). From the soil microstructure image obtained in this study, it was seen that there were more soil debris, less soil pores and more compact contact between soil bone particles and soil matrix in CK treatment.

However, there was a microstructure distribution of flocculated mass in soil of T1 treatment. Besides, soil of T1 treatment possessed a loose contact between bone particles and soil matrix, more pores with larger pore size. In addition, soil debris with T2 and T3

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treatment were apparently lower than that of CK treatment. From initial analysis, there were a certain number of organic suspended particles in biogas slurry which entered into the soil with water during the irrigation process. Later on those were absorbed at the surface of soil particles and could be considered as input of exogenous organic matter. In the meantime, appropriate biogas slurry irrigation made microbial activities of crop root and enzyme catalyzed reactions active. This had contributed to the formation of soil aggregation and further enhanced water saturated water conductivity.

Application of fertilizer or CK treatment didn't possess the input of exogenous organic matters. In those, the enhancement of soil organic matter occurred due to rapid increase of soil effective nutrient content which quickly satisfied the nutritional demand of crop growth and development. Thus, a higher crop biomass as well as the resultant input of soil organic matter were obtained (Lee et al., 2009), which did not have a promotion effect for the formation of soil aggregation and pore.

Conclusions

(1) Compared with CK (the inorganic fertilizer) treatment, T1 (biogas slurry volume concentrations of 20%) treatment could provide more stable nutrient supply to tomato crop over the growth period, keeping LAI, photosynthetic rate, and leaf chlorophyll (a+b) content at a relatively stable level in tomato growth stage.

(2) T1 treatment could obtain yield which was comparable with that of CK treatment. T1 and T2 (biogas slurry volume concentrations of 15%) treatments could not only obtain higher absolute contents of soluble sugar and the titrate acid but also better coordinated the sugar acid ratio, whereas T3 treatment was adverse to the formation of tomato nutritional quality.

(3) In tomato seedling stage, N fertilizer application amount or biogas slurry concentration could be decreased appropriately. From the stage of blossoming and fruiting to fruit maturity stage, T1 and CK treatment could both increase N content in soil. The increase amplitude of T1 treatment was a little smaller (0.007 and 0.004 g/kg in spring and fall cultivation, respectively) than that of CK treatment (0.117 and 0.216 g/kg of CK treatment). This illustrates the much more stable trend which was appropriate for a long term application. N content in soil of T2 and T3 treatments decreased dramatically from the stage of blossoming and fruiting to fruit maturity stage.

(4) Each treatment could increase soil organic matter content, whereas the increase amplitudes of soil organic matter as well as soil saturated water hydraulic conductivities of T1 and T2 treatments were all higher than those of CK treatment. This illustrates that T1 and T2 treatment could be more effective to increase soil organic matter content and thus improve soil water holding capacity. Compared with CK treatment, different treatments with biogas slurry could increase the number of soil aggregates, decrease soil debris and increase the number of soil pores, wherein T1 treatment had the most apparent effect.

In all, T1 (biogas slurry volume concentrations of 20%) treatment could provide more stable nutrient supply for the growth and development of tomato. While not only obtaining the yield comparable with that of traditional fertilizer treatment but also improving tomato nutritional quality. T1 treatment improved soil environmental conditions, which could be used as reference for the replacement of fertilizer with biogas slurry.

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The effects of different biogas slurry irrigation amounts on crop growth, fruit quality and soil environment, also the effects on other crops should be explored in future studies.

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