Effects and evaluation of biogas slurry/water integrated irrigation technology on the growth, yield and quality of tomatoes

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Abstract: Reasonable techniques and methods in biogas slurry application are significant for the promotion of biogas slurry and the improvement of crop quality in agricultural production. To investigate the impacts of different biogas slurry application techniques on the water use efficiency, growth, yield, and quality of tomatoes, three irrigation techniques, and two application methods were considered in this study. The three irrigation techniques are alternate partial root-zone irrigation (APRI), fixed partial root-zone irrigation (FPRI), and two sides root-zone irrigation (TSRI). Two application methods refer to applying the biogas slurry with hole irrigation and surface irrigation. In addition, principal component analysis (PCA) and technique for order preference by similarity to ideal solution (TOPSIS) methods were adopted to evaluate the comprehensive quality and comprehensive indicators of tomatoes among different treatments. There are three hole irrigation treatments, T1 (APRI), T2 (TSRI), T3 (FPRI), and three surface irrigation treatments, T4 (APRI), T5 (TSRI), and T6 (FPRI) were set in two-season pot experiments. The results show that the plant height, dry matter accumulation, fruit yield, and water use efficiency present a similar descending trend for APRI, TSRI, and FPRI under the same methane irrigation method, yet show that the hole irrigation treatment was higher than the surface irrigation treatment for the same irrigation technique. These indicate that the coupling of APRI technique and hole irrigation is more conducive to the increase of plant production and water use efficiency. Meanwhile, T1 treatment can significantly improve the soluble sugar, sugar-acid ratio, VC content, soluble protein, soluble solid content, and firmness of tomato fruits, which are better for the taste, storage, and transportation of tomato fruit. The titratable acid content in tomato fruit is the highest in T2 treatment, followed by T5 treatment, indicating that TSRI technique may result in an accumulation of titratable acid and is not conducive to the taste of the tomato. The comprehensive nutritional quality and index evaluation results show that T1 treatment ranks the highest among all treatments, and can be used as an optimal irrigation method for the implementation of integrated water/biogas slurry.

Keywords: biogas slurry, irrigation technique, coupling, quality evaluation, comprehensive index evaluation
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1 Introduction

To ensure higher crop productivity and economic benefit, more and more chemical fertilizers have been applied to agricultural production[1], which however has caused such problems as soil compaction, acidification, and secondary salinization[2]. By contrast, organic fertilizer can improve the soil environment, increase soil fertility, the content of organic matter[3], and soil microbial activity[4], and is conducive to the increase in crop yield and quality as well as the sustainable use of soil.

Biogas slurry is a by-product of biogas engineering, which is rich in water and nutrients, can be used as a high-quality quick-acting organic fertilizer, and can easily enter into the root-zone for crop absorption for its good water solubility[5]. Moreover, biogas slurry also contains a variety of organic active substances such as microelements, microorganisms, and humic acid that are beneficial to the soil environment and crop growth[6]. Studies have shown that the application of biogas slurry in agriculture production can significantly increase soil organic matter content[7], improve crop quality[8], maintain soil fertility[9], and facilitate the formation of soil aggregate structure. Nevertheless, biogas slurry is a mass with high water content and low fertility[10], making it easy to produce surface runoff or deep leakage when applied by traditional irrigation methods, which will reduce the water and fertilizer use efficiency. Therefore, reasonable irrigation techniques are very important for the good use of water and biogas slurry together.

Surface irrigation and hole irrigation are two commonly used methods for liquid fertilizer application[11]. Studies have shown that biogas slurry applied by hole irrigation has a higher water and fertilizer use efficiency than surface irrigation, however, there is a likelihood of deep leakage due to its characteristics of high water content and low fertility. It is necessary to carry out studies on the coupling technology of biogas slurry application methods and advanced irrigation techniques, such as Alternate Partial Root-zone Irrigation (APRI)[12]. So far, significant insights into the benefits of APRI technique on crop production have been gained[13-16] since

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it was first proposed in the 1990s[17]. However, there still exist some questions needing to be dealt with: (i) most studies have paid attention to the effects of APRI technique on drip irrigation and surface irrigation, such as Wang et al.[18] applied the APRI-drip irrigation technology to the study of tomato growth and Siyal et al.[19] applied the APRI-surface furrow irrigation technology to the study of the water use efficiency of okra. A study on the APRI technique used in hole irrigation is still lacking. Especially, there is a lack of comparison among the APRI hole irrigation, and the hole irrigation fixed on one side of the crop and two sides of the crop (TSRI and FPRI), which may deepen our understanding of the characteristics and effects of the irrigation technique; (ii) the medium irrigated in current studies on APRI technique are all water and chemical fertilizer, studies on the coupling use of this technique and biogas slurry are still not available; (iii) most studies have qualified the effects of APRI technique on crop growth, yield, quality, and water use efficiency, but there lacks a comprehensive evaluation on total quality and comprehensive benefits of the crop, especially under the condition of integrated use of water and biogas slurry together, which may give us in-depth knowledge about the advantages of biogas slurry and will be very useful to promote its application.

To fill the above gaps, a systematic investigation is carried out on the effects of biogas slurry ARPI, TSRI, and FPRI on tomato physiological indicators, yield, quality, and water use efficiency in the present study. Both the surface irrigation and hole irrigation methods are adopted in two-season pot experiments, water and biogas slurry are irrigated at the same time. Comprehensive evaluation methods of PCA and TOPSIS are used to assess the total quality and comprehensive benefits of tomatoes, and then the optimal combination of irrigation technique and biogas slurry application method are obtained. The results will provide some help for the suitable application of biogas slurry, which will be useful for the efficient utilization of biogas slurry and a reduction of chemical fertilizer use, and finally good for agricultural sustainable development.

2 Materials and methods

2.1 Experimental site

The experiment was conducted in a vegetable cultivation greenhouse (36°01'N, 103°46'E) of the water-fertilizer integrated irrigation experiment center in Weiling country, Qilihe District, Lanzhou City of Gansu Province with an altitude of 1835.7 m. This area belongs to the temperate continental climate with year-round drought, scarce rainfall, and sufficient sunshine. The average annual temperature is 10.3°C, the temperature difference between day and night is 12°C-18°C, and the frost-free period lasts about 150 d. The average annual precipitation and evaporation were 327 mm and 1158.0 mm, respectively. The greenhouse has a ridge structure, and its length, width, and height are 50 m, 10.5 m, and 4 m, respectively. The greenhouse is equipped with small automatic weather information collection equipment, which can continuously monitor meteorological data.

2.2 Experimental materials

Tomato (*Solanum lycopersicum* L.) cultivar "Zhongyan 958F1" was selected in pot culture experiments.

The biogas slurry adopted in the experiment was collected from the biogas tank of the Holstein Dairy Cattle Breeding Center of Lanzhou City. Cattle manure was used as the fermentation raw materials, and the anaerobic process was conducted at a constant temperature of 37°C. The biogas slurry was taken samples directly after the anaerobic digestion, stored at a normal temperature condition for about two months, and then its physical and chemical properties were analyzed. Further, the biogas slurry was applied to the plant after it was filtered and sterilized. It should be noted that the biogas slurry was placed in a plastic bucket and left open to settling for two months before the experiment, when used the upper clear liquid was taken and the larger suspended particles were filtered out using 4 layers of gauze of 32 mesh. Meanwhile, the relevant physical and chemical properties of the biogas slurry were measured every seven days during the test to ensure the basic stability of the physical and chemical properties of the biogas slurry used during the test period. The main characteristics of the biogas slurry were: total nitrogen (N) 1.038 g/L, total phosphorus (P) 0.553 g/L, total potassium (K) 1.201 g/L, organic matter content 10.65 g/L, pH 7.89, the conductivity 23.59 dS/m, and the viscosity 1.869×10^{-3} Pa·s.

The soil was air-dried naturally before sifting by a 2 mm sieve preparing for the later pot experiment use. The soil type belongs to loamy clay, of which the contents of sand, silt, and clay were 38.92%, 21.06%, and 40.02%, respectively. The average soil bulk density was 1.35 g/cm^3, and the field water holding rate was 20% (mass moisture content).

2.3 Experimental design

Two biogas slurry application methods, i.e., biogas slurry hole irrigation and biogas slurry surface irrigation, as well as three irrigation techniques, i.e., Alternate Partial Root-zone Irrigation (APRI), Fixed Partial Root-zone Irrigation (FPRI), and Two Sides Root-zone Irrigation (TSRI) were considered in the experiments. Thus, there are six treatments in total, three-hole irrigation treatments, T1 (APRI), T2 (TSRI), T3 (FPRI), and three surface irrigation treatments, T4 (APRI), T5 (TSRI) and T6 (FPRI) were set in both the two-season pot experiments, as shown in Table 1.

Table 1 Experimental design

Treatment	Irrigation method	Irrigation technique
T1	Hole irrigation	APRI
T2		TSRI
T3		FPRI
T4	Surface irrigation	APRI
T5		TSRI
T6		FPRI

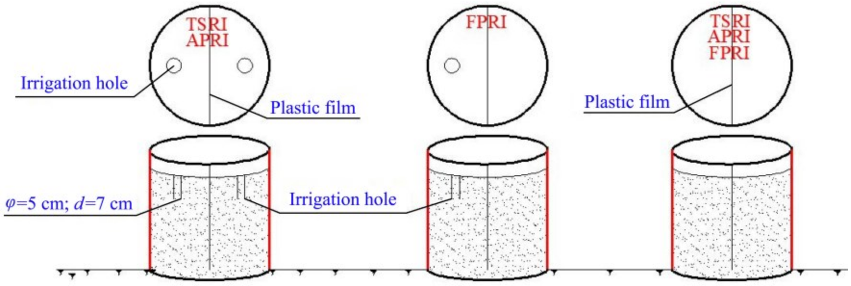
Note: APRI: Alternate Partial Root-zone Irrigation; TSRI: Two Sides Root-zone Irrigation; FPRI: Fixed Partial Root-zone Irrigation.

The experiment was started on March 20, 2018, and September 1, 2018, and finished on July 26, 2018, and December 30, 2018, respectively. The tomato plants were transplanted when they grow to have three leaves. 2000 mL water was irrigated for each plant to make a good survive after transplanting. The growth period of the plant was divided into four stages, namely, the seedling period, flowering period, fruit enlarging period, and fruit maturity period.

The diameter and depth of the pot are 17 cm and 30 cm. Drain holes were set at the bottom of each pot, and the plastic film was covered at the surface of the pot after the plant was transplanted. Meanwhile, a thick plastic film was placed vertically in the middle of the pot to separate the pot into two parts; the aim of the plastic film is to prevent the water on both sides of the pot from interpenetrating. A V-shaped notch was cut out in the middle of the film to make the planting of tomato seedlings planting. When tomato seedlings were transplanted, the roots were artificially distributed symmetrically on the left and right sides of the V-shaped notch in the middle of the pot.

For hole irrigation, the holes were symmetrically arranged on both sides of the plastic film, while for fixed partial root-zone irrigation, they were just arranged on one side (the left side in this experiment). The hole center was 5 cm away from the plant root, and the diameter and depth were 5 cm and 7 cm, respectively. The detail of the hole can refer in Figure 1, and the photographs of the pot experiment are shown in Figure 2.

Water and biogas slurry/water mixture (concentration 20%) were irrigated alternatively at an irrigation frequency of 2 d^{-1}. The irrigation amount is referenced by the evaporation amount of the evaporating dish, calculated as W=1.8E_p·S. Here, 1.8 is the crop-evaporating dish coefficient; E_p is the evaporation amount of the evaporating dish within two irrigation intervals; S is the surface area of the pot. In this experiment, the type φ-20 evaporating dish was used, which was placed at the same height as the crop canopy in the greenhouse, and the height was adjusted with the growth of tomato plants. The water amount irrigated for plants in treatments of APRI and FPRI was 70% of that in TSRI treatment. All treatments were carried out with three replicates.



a. Details of the hole and sketch map for TSRI and APRI b. Sketch map for FPRI c. Sketch map for surface irrigation

Note: The pot is separated into two parts with an impenetrable middle layer made of plastic film. TSRI: Two Sides Root-zone Irrigation; APRI: Alternate Partial Root-zone Irrigation; FPRI: Fixed Partial Root-zone Irrigation.

Figure 1 Schematic diagram of the hole irrigation and surface irrigation

Figure 2 Photographs of tomato pot experiment

2.4 Indices and measurement methods

2.4.1 Plant growing measurements

The measurement began on the first day after planting and was measured and recorded every 4 d. The plant height was measured from the bottom of the stem with a meter ruler. The stem diameter was measured with an electronic caliper (precision: 0.01 mm).

2.4.2 Dry matter mass

The dry matter mass was measured by the oven-drying method. Random samples were taken at the end of each growth period (3 plants for each treatment). The roots, stems, leaves, and fruits were separately weighed for fresh quality. Subsequently, they were placed in an oven at 105°C for 2 h, and then dried at a constant temperature of 75°C. Finally, the dry matter masses of roots, stems, leaves, and fruits were measured by an electronic scale with a precision of 0.01 g, respectively. The division of the growth period of tomatoes is listed in Table 2.

Table 2 Division of tomato growth period

Growing periods	Growth period of tomato (month/day)			
	Seeding period	Flowering period	Fruit enlarging period	Fruit maturity period
Spring of 2018	03/20-04/13	04/14-05/01	05/02-06/02	06/03-07/26
Autumn of 2018	09/01-09/22	09/23-10/11	10/12-11/08	11/09-12/30

2.4.3 Tomato quality and yield

Fruit firmness was measured with a Gy-1 hardness tester[20]. Soluble solids were determined by a WAY-2S Abbe refractometer[21]. Vitamin C content was detected by Molybdenum blue colorimetric method[22], soluble total sugars were tested by Anthrone method[23], organic acids were determined by acid-base titration[24], and soluble proteins were determined by Coomassie Brilliant Blue G-250 staining method[25]. For each treatment, 3 plants were selected to calculate the tomato yield and quality. The mass of a single fruit was measured with an electronic balance (precision: 0.01 g), and the yield of each treatment was calculated with the average mass of the three plants.

2.4.4 Water use efficiency (WUE)

$$\mathrm{WUE}=Y_a/I_a \tag{1}$$

where, WUE is water use efficiency, kg/m^3; Y_a is the yield per plant, kg; I_a is irrigation amount, mL.

2.4.5 Evaluation method

The comprehensive quality of tomato was evaluated by principal component analysis (PCA)[26]. The comprehensive benefit of tomato was assessed by Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) [27].

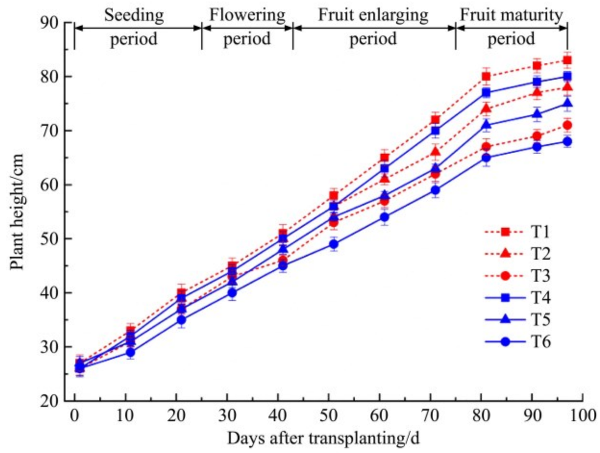
2.5 Data processing and analysis

Data processing, calculation, and chart making were completed through Excel 2019 and Origin 9.0. Significant difference analyses among different treatments, principal component analysis, and comprehensive benefit analysis based on TOPSIS were realized by SPSS 24.0.

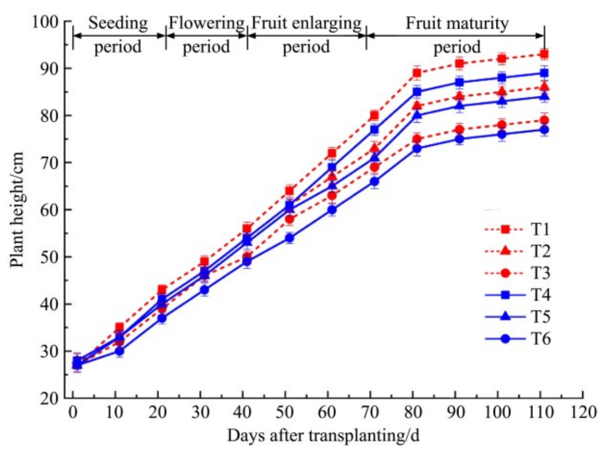
3 Results

3.1 Effects on plants height of tomato

Figure 3 presented the growing trend of plant height of tomato at different growing periods of the two season experiments. It can be seen that the tomato plant height was the largest in T1 treatment (83 cm in spring; 93 cm in autumn), and the smallest in T6 treatment (68 cm in spring; 77 cm in autumn). There were similar trends among various treatments in the investigated two seasons, presenting a descending trend for T1, T4, T2, T5, T3, and T6. For treatments with hole irrigation, the plants height of T1 treatment in fruit maturity period increased relatively by 6.0% and 14.5% in spring season when compared with T2 and T3 treatments, which were 7.5% and 15.1% in autumn, respectively. For treatments with surface irrigation, the plants height of T4 treatment in fruit maturity period increased relatively by 6.3% and 15.0% in spring and 5.6% and 13.5% in autumn experiment when compared with T5 and T6 treatments. The highest value of plants height in T1 and T4 treatments indicated that APRI was more conducive to plant growth than TSRI and FPRI both under hole and surface irrigation of biogas slurry. For the same irrigation technique (APRI, TSRI, or FPRI), the plant height among treatments of hole irrigation and surface irrigation showed the trends of T1>T4, T2>T5 and T3>T6, and a 3.8%, 3.6%, and 4.2% higher in spring and about 2.3%, 4.3%, and 2.5% higher in autumn, which illustrated that the application of biogas slurry with hole irrigation was better for tomato growth. The differences in plants height among treatments are more serious may be due to the increasing demand for nutrients and water in the fruit enlarging and maturity period, and the benefits of the advantages of irrigation method are more obvious.



a. Spring of 2018

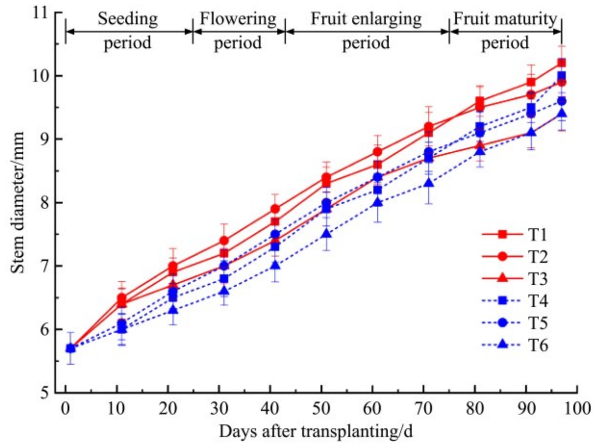


b. Autumn of 2018

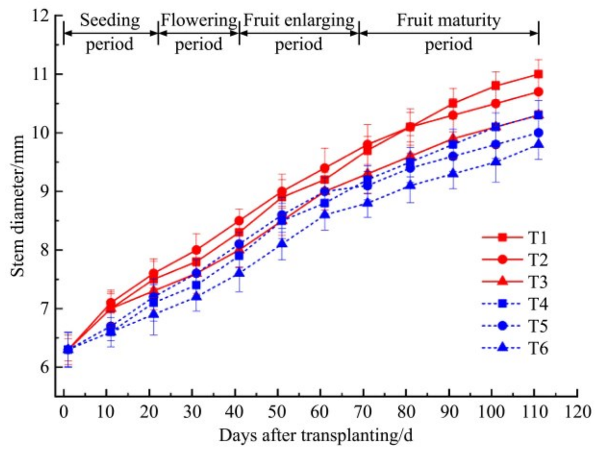
Figure 3 Effects of different treatments on plants height of tomato

3.2 Effects on stem diameter of tomato

It can be observed from Figure 4 that at the end of the growth period, the stem diameter of tomato in T1 treatment was the largest, which were 10.2 mm in spring and 11.0 mm in autumn, and that in T6 treatment was the smallest (9.4 mm in spring; 9.8 mm in autumn). For treatments with hole irrigation, the stem diameters of T1 treatment were 2.9% and 7.8% higher than T2 and T3 treatments in spring, and 2.7% and 6.4% higher in autumn, respectively. For treatments with surface irrigation, the stem diameters in T4 treatment exceeded the T5 and T6 treatments by 4.0% and 6.0% in spring and 2.9% and 4.9% in autumn, respectively. These indicated that APRI was more conducive to the increase in the stem diameter and finally for the healthy growth of plants than TSRI and FPRI. Under the same irrigation technology (APRI, TSRI or FPRI), the stem diameters for treatments under hole irrigation of biogas slurry were larger than those in treatments with surface irrigation, namely T1>T4, T2>T5, and T3>T6 by 2.0%, 3.1% and 1.0% in spring, and 6.4%, 6.5% and 4.9 in autumn, respectively. This indicated that the application of biogas slurry with hole irrigation could harden seeding and promote better growth of tomato plants than surface irrigation.



a. Spring of 2018



b. Autumn of 2018

Figure 4 Effects of different treatments on stem diameter of tomato

3.3 Effects on dry matter mass, roots distribution and root-shoot ratio

3.3.1 Total dry biomass accumulation and aboveground biomass

The total dry biomass accumulation and aboveground biomass presented significant differences of a single tomato plant under various treatments. The data were obtained at the end of the growth period of tomato. As shown in Table 3, the plants in T1 treatment has the largest total dry biomass, which was 104.11 g in spring and 110.75 g in autumn, and that in T6 treatment were the smallest, 71.40 g in spring and 78.46 g in autumn, respectively. Moreover, the total dry biomass accumulation and the aboveground biomass both presented a descending trend for T1, T4, T2, T5, T3 and T6. For treatments with hole irrigation, the total dry biomass accumulation of plants in T1 treatment was increased by 13.6% and 30.4% than that in T2 and T3 treatments in spring, and increased by 16.0% and 30.8% than T2 and T3 treatments in autumn. Meanwhile, Compared with T5 and T6 treatments, T4 treatments increased the total dry biomass accumulation of plants by 15.6% and 30.9% in spring and by 18.0% and 28.1% in autumn. These results indicated that APRI could better enhance the total dry biomass accumulation and aboveground biomass when compared with TSRI and FPRI techniques. Under the same irrigation technique (APRI, TSRI or FPRI), hole irrigation was superior to surface irrigation in both the total dry biomass accumulation and aboveground biomass of single tomato plant, and there were the trends of T1>T4, T2>T5 and T3>T6. The total dry biomass of plant in treatment with hole irrigation were 11.4%, 13.3%, and 11.7% higher than that with surface irrigation in spring and 10.2%, 12.1%, and 7.9% in autumn. These indicated that hole irrigation could promote the accumulation of total dry biomass and aboveground biomass than surface irrigation.

3.3.2 Roots dry biomass

Similarly, it can be seen from Table 3 that the dry biomass of tomato roots in both seasons presented a descending trend for T1, T2, T3, T4, T5 and T6. For treatments with hole irrigation, the dry biomass of tomato roots in T1 treatment were 3.3% and 22.4% higher than T2 and T3 treatments respectively in spring, and 2.0% and 15.8% in autumn. When compared with T5 and T6 treatments, the dry biomass of tomato roots in T4 treatment were 5.9% and 24.1% higher in spring, and 8.6% and 14.0% higher in autumn, indicating that APRI technique can effectively promote the growth of tomato root system. Under the same irrigation techniques (APRI, TSRI or FPRI), the root dry biomass of plants with hole irrigation was larger than that with surface irrigation, namely T1>T4, T2>T5, and T3>T6, by 24.6%, 21.5% and 23.2% correspondingly in spring, and by 23.6%, 15.8% and 14.0% in autumn. This conclusion can be drawn that hole irrigation was better than surface irrigation at promoting the growth of tomato roots.

A comparative analysis of the dry root biomass in the upper soil layer (0-15 cm) and the lower soil layer (15-30 cm) of each treatment was shown in Table 3, and results presented that the root dry biomass in the upper soil layer of all treatments were greater than that in the lower soil. In addition, the root dry biomass of both the upper and lower soil layers were the largest for plants in T1 treatment (1.95 g and 1.33 g in spring; 2.04 g and 1.31 g in autumn), while the smallest for plants in T6 treatment (1.32 g and 0.69 g in spring; 1.61 g and 0.82 g in autumn). In the two-season experiments, the upper-to-lower layer ratios of root dry biomass among all treatments were the highest in T5 (2.57, spring; 2.38, autumn), and T1 was the lowest (1.47, spring; 1.56, autumn), indicating that the irrigation method adopted in T1 treatment could promote the roots growing downward, which is a benefit to take the root below and make the plant grow lustily.

Table 3 Effects of different treatments on dry biomass and root of a single tomato plant

Growing periods	Index	T1	T2	T3	T4	T5	T6
Spring of 2018	Total dry biomass/g	104.11^a	91.64^c	79.75^d	93.46^b	80.87^d	71.40^e
	Aboveground biomass/g	39.17^a	33.82^c	32.17^d	35.18^b	31.54^d	29.56^e
	Total root weight/g	3.28^a	2.69^b	2.55^c	2.49^c	2.18^d	2.01^e
	Root/shoot	0.084	0.080	0.079	0.071	0.069	0.068
	Dry weight of fruit/g	61.66^a	55.13^b	45.03^d	55.79^b	47.15^c	39.83^e
	Root dry weight (0-15 cm)/g	1.95^a	1.68^b	1.53^c	1.62^b	1.57^{cb}	1.32^d
	Root dry weight (15-30 cm)/g	1.33^a	1.01^b	1.02^b	0.87^c	0.61^d	0.69^d
	Root weight ratio (Upper/lower)	1.47	1.66	1.50	1.86	2.57	1.91
Autumn of 2018	Total dry biomass/g	110.75^a	95.46^c	84.68^d	100.49^b	85.13^d	78.46^e
	Aboveground biomass/g	41.15^a	39.56^c	34.82^d	40.02^b	38.15^{bc}	35.89^c
	Total root weight/g	3.35^a	3.23^a	2.76^b	2.87^b	2.67^{bc}	2.43^d
	Root/shoot	0.084	0.082	0.079	0.072	0.070	0.068
	Dry weight of fruit/g	66.25^a	52.67^c	47.1^d	57.6^b	44.312^{cd}	40.14^e
	Root dry weight (0-15 cm)/g	2.04^a	2.01^a	1.71^c	1.92^b	1.88^b	1.61^d
	Root dry weight (15-30 cm)/g	1.31^a	1.22^b	1.05^c	0.95^d	0.79^e	0.82^e
	Root weight ratio (Upper/lower)	1.56	1.65	1.63	2.02	2.38	1.96

Note: a, b, c, d, and e respectively represent the significant differences among the same indexes of different treatments at p = 0.05 level.

3.3.3 Root-shoot ratio

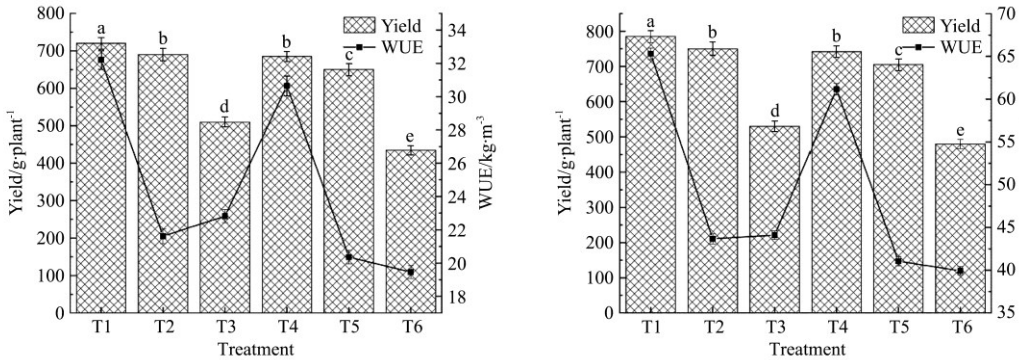
There were similar change trends for root-shoot ratio of plants among various treatments in the investigated two-season experiments. It can be seen from Table 3 that plants in T1 treatment obtained the largest root-shoot ratio, which was 0.084 in both spring and autumn experiments, and the smallest were planted in T6 treatment, which was 0.068 in both two seasons. Furthermore, the tomato root-shoot ratio in the two seasons presented a descending trend for T1, T2, T3, T4, T5, and T6. For treatments with hole irrigation, the root-shoot ratio showed T1>T2>T3 and T4>T5>T6, indicating that APRI could better facilitate the accumulation of dry biomass of plant roots when compared with TSRI and FPRI. Under the same irrigation techniques (APRI, TSRI or FPRI), the root-shoot ratio presented the trends of T1>T4, T2>T5, and T3>T6, indicating that the application of biogas slurry with hole irrigation had a larger contribution to the accumulation of root of plant. On the whole, both the above-ground total dry matter mass and root dry mass of tomato obtained maximum values under the T1 (BHI+APRI) treatment, indicating that the T1 treatment could effectively promote the growth of tomatoes in both above-ground and below-ground parts. This is mainly due to the fact that the aboveground canopy and belowground root parts are two interdependent and interacting systems. During changes in soil conditions, the root system provides the canopy with sufficient water and mineral nutrients to ensure the normal growth of the above-ground parts, while the canopy provides the root system with photosynthetic and assimilative substances to promote the growth of the root system, which plays a role in balancing the above- and below-ground biomass.

3.4 Effects on yield, water use efficiency, and quality of tomato

3.4.1 Yield and water use efficiency

It can be seen from Figure 5 that plants in T1 treatment had the highest yield, followed by T2 and T4 treatments, however, there was no significant difference between the plants of T2 and T4 treatments (p=0.05), while plants in T6 treatment had the lowest yield of tomato. For treatments with hole irrigation, the tomato yield in T1 treatment was increased by 4.35% and 41.18% in spring, and 4.67% and 48.11% in autumn when compared to that of T2 and T3 treatments, respectively. Similarly, as compared with T5 and T6 treatments, the spring yield of tomato in T4 treatment increased by 5.38% and 57.47%, and the autumn yield by 5.25% and 54.58%, respectively. These indicated that APRI was more conducive to the development of tomato fruit than TSRI and FPRI. For the same irrigation techniques (APRI, TSRI or FPRI), the application of biogas slurry with hole irrigation is superior to that of surface irrigation, and the tomato yields in T1, T2, T3 treatments were respectively 5.11%, 6.15%, and 17.24% higher than that in T4, T5, and T6 treatments in spring, and 5.79%, 6.38%, and 10.42% in autumn. It indicated that the application of biogas slurry with hole irrigation could better enhance the yield of tomatoes than that of surface irrigation.

Water use efficiency (WUE) is significantly affected by irrigation techniques. It can be seen from Figure 5 that APRI had obvious advantages in improving the water use efficiency of tomatoes when compared with TSRI and FPRI. Specifically, the WUE of plants in T1 treatment were 49.05% and 41.15% higher than that of T2 and T3 treatments in spring and 49.52% and 48.09% in autumn. As compared with T5 and T6 treatments, the WUE of plants in T4 treatment were 50.54% and 57.50% higher in spring, and 48.93% and 53.10% higher in autumn. For treatments with the same irrigation technique, APRI, TSRI or FPRI, the application of biogas slurry with hole irrigation showed great advantages over surface irrigation, the WUE of tomato in T1 treatment were 5.09% and 6.80% higher than T4 treatment in two seasons, respectively, that were 5.09% and 6.38% of T2 treatment higher than T5 treatment, as well as a 17.27% and 10.42% higher in T3 treatment than T6 treatment.



a. Spring of 2018 b. Autumn of 2018

Note: a, b, c, d, and e respectively represent the significant differences among the same indexes of different treatments at p=0.05 level.

Figure 5 Yield and water use efficiency of tomato under various treatments

3.4.2 Tomato quality

Table 4 shows the nutritional and quality indices of tomatoes under various treatments. It can be seen from Table 4 that the T1 treatment had the highest soluble sugar, sugar-acid ratio, vitamin C content, soluble protein, soluble solids, and firmness among all treatments, except for the titratable acid. For the same irrigation method, i.e., hole irrigation and surface irrigation, the soluble sugar, sugar-acid ratio, vitamin C content, soluble protein, soluble solids, and firmness all showed the trends of T1>T2>T3 and T4>T5>T6. However, it should be noticed that the titratable acid presented the trend of T2>T1>T3 and T5>T4>T6. These indicated that compared with TSRI and FPRI, APRI was more conducive to the improvement in soluble sugar, sugar-acid ratio, VC content, soluble protein, soluble solids, and firmness, while TSRI increased the accumulation of titratable acid, which to some extent will influence the taste of tomato. Under the same irrigation technique (APRI, TSRI, or FPRI), water/biogas slurry integrated applied with hole irrigation was better than that with surface irrigation in all quality indexes, showed the trends of T1>T4, T2>T5, and T3>T6, indicating that the hole irrigation of integrated water/biogas slurry was more conducive to the improvement of tomato fruit quality than surface irrigation.

Table 4 Effects of various treatments on tomato quality

Growing periods	Treatment	Titratable acid/%	Soluble sugar/%	Sugar/Acid ratio	Vitamin C /mg·100 g^{-1}	Soluble protein /mg·g^{-1}	Soluble solids/%	Firmness /kg·cm^{-2}
Spring of 2018	T1	0.322^{ab}	3.314^{a}	10.292	20.353^{a}	1.036^{a}	6.03^{a}	7.03^{a}
	T2	0.331^{a}	3.283^{ab}	9.918	19.926^{b}	1.015^{b}	5.96^{ab}	6.90^{b}
	T3	0.274^{cd}	2.711^{d}	9.894	19.027^{d}	0.961^{d}	5.81^{de}	6.60^{d}
	T4	0.287^{bc}	2.918^{b}	10.167	19.457^{c}	0.992^{c}	5.89^{bc}	6.78^{c}
	T5	0.293^{b}	2.815^{c}	9.607	19.136^{d}	0.972^{d}	5.85^{cd}	6.70^{c}
	T6	0.266^{d}	2.401^{e}	9.026	18.756^{e}	0.95^{e}	5.77^{e}	6.55^{d}
Autumn of 2018	T1	0.329^{ab}	3.344^{a}	10.164	20.733^{a}	1.105^{a}	5.80^{a}	7.28^{a}
	T2	0.341^{a}	3.273^{abc}	9.598	20.276^{b}	1.085^{b}	5.73^{b}	7.16^{b}
	T3	0.299^{c}	2.801^{e}	9.368	19.367^{e}	1.029^{d}	5.58^{c}	6.88^{de}
	T4	0.317^{bc}	3.108^{c}	9.804	19.827^{c}	1.061^{c}	5.66^{bc}	7.01^{bc}
	T5	0.311^{c}	2.945^{d}	9.469	19.536^{d}	1.038^{d}	5.62^{bc}	6.94^{c}
	T6	0.293^{c}	2.481^{f}	8.468	19.116^{f}	1.021^{e}	5.54^{c}	6.83^{e}

Note: a, b, c, d, and e respectively represent the significant differences among the same indexes of different treatments at p=0.05 level.

3.5 Evaluation of tomato quality and comprehensive benefit

3.5.1 Tomato quality evaluation

To explore the impacts of various water/biogas slurry irrigation techniques on tomato fruit quality, the principal component analysis (PCA) method was used to obtain the comprehensive nutritional quality based on the single nutritional quality of tomato in Table 4. The fruit water content (X_1), soluble sugar (X_2), titratable acid (X_3), sugar/acid ratio (X_4), vitamin C (X_5), soluble protein (X_6), soluble solids (X_7) and fruit firmness (X_8) were adopted as the evaluation indices in the PCA, and the components with a cumulative variance contribution rate of over 85% were used as the main principal components, which meet the standard of great than 80% in PCA method[24,28]. In the present study, two principal components F_1 and F_2 were extracted, and the results were shown in Table 5. As can be seen from Table 5, the variance contributions of the first principal component (F_1) and the second principal component (F_2) in the spring experiments were 81.347% and 12.829%, respectively, and the cumulative variance contribution was 94.176%. The variance contributions of F_1 and F_2 in the autumn experiment were 79.16% and 13.835%, respectively, and the cumulative variance contributions were 92.995%. Since the cumulative variance contribution of the extracted principal components was great than 90% in the two seasons, they could replace the original 8 variables in evaluating the comprehensive quality of tomato without losing the original important data information.

Table 5 Main components and scoring function of tomato comprehensive quality evaluation

Growing periods	Principal component analysis and scoring function
Spring of 2018	F_1=0.296 X_1+0.370X_2+0.382X_3+0.203X_4+0.379X_5+0.384X_6+0.385X_7+0.386X_8
	F_2=0.4X_1–0.237X_2+0.18X_3+0.797X_4–0.208X_5–0.17X_6–0.16X_7–0.142X_8
	F=0.864F_1+0.136F_2
Autumn of 2018	F_1=0.296 X_1+0.366X_2+0.381X_3+0.215X_4+0.387X_5+0.386X_6+0.389X_7+0.384X_8
	F_2=0.531X_1–0.273X_2+0.159X_3+0.713X_4–0.154X_5–0.166X_6–0.121X_7–0.19X_8
	F=0.851F_1+0.149F_2

Table 6 Evaluation score of tomato comprehensive quality under biogas irrigation technology and mode

Growing periods	Treatment	F_1	F_2	F	Rank
Spring of 2018	T1	3.210	9.822	2.631	1
	T2	2.140	7.390	1.706	2
	T3	−2.155	−0.631	−1.823	5
	T4	0.792	5.847	0.894	3
	T5	−0.503	1.512	−0.294	4
	T6	−3.483	−2.940	−3.115	6
Autumn of 2018	T1	3.317	−0.488	2.751	1
	T2	1.984	−1.030	1.536	2
	T3	−2.125	−0.172	−1.834	5
	T4	0.721	1.494	0.836	3
	T5	−0.606	1.076	−0.355	4
	T6	−3.291	−0.880	−2.932	6

The first and second principal components are used to construct the comprehensive principal component function F, according to which the quality score and rank are calculated (as shown in Table 6). From Table 6, it can be seen that the comprehensive quality score of tomato was the best under T1 treatment, 2.631 (spring) and 2.751 (autumn), and the worst under T6 treatment, –3.115 (spring) and –2.932 (autumn). The comprehensive quality scores under the treatments followed a descending trend for T1, T2, T4, T5, T3 and T6. It indicated that APRI could enhance the comprehensive quality of tomatoes under the same irrigation method, and water/biogas slurry hole irrigation contributed greater to tomato quality than surface irrigation. Overall, T1 treatment obtained the best comprehensive quality of tomato.

3.5.2 Comprehensive benefit evaluation of tomato

The growth, yield, WUE, and comprehensive nutritional quality are important factors that affect the comprehensive benefit of tomatoes. In order to evaluate the effects of various irrigation treatments on tomato growth and yield and quality more comprehensively, plant height, stem thickness, total dry biomass, fruit water content, soluble sugar, titratable acid, sugar-acid ratio, vitamin C, soluble protein, soluble solids, firmness, yield, and WUE were selected as the evaluation indicators in TOPSIS method to make a comprehensive benefit evaluation among treatments. Table 7 shows the comprehensive benefit evaluation results, in which D_j^+ and D_j^- respectively represent the weighted distance between the solution of each treatment and the positive ideal solution and the negative ideal solution. C_j is a comprehensive evaluation index for tomato of each treatment, and the ranking is based on the value of C_j. As can be seen in Table 7, T1 treatment had the best comprehensive benefits in the two seasons experiments, with C_j value were 0.840 in spring and 0.901 in autumn respectively, followed by T4 treatment, T6 treatment was the worst, with C_j value only 0.019 in spring and 0.064 in autumn. For treatments with hole irrigation and surface irrigation separately, the ranking of the comprehensive index evaluation score among treatments showed the trends of T1>T2>T3 and T4>T5>T6. Under the same irrigation techniques (APRI, TSRI or FPRI), the ranking of the comprehensive benefit score exhibited T1>T4, T2>T5, and T3>T6, indicating that T1 treatment could obtain the optimal comprehensive index evaluation.

Table 7 Comprehensive benefit analysis of tomato under different treatments

Growing periods	Treatment	D_j^+	D_j^-	C_j	Rank
Spring of 2018	T1	0.008	0.043	0.840	1
	T2	0.024	0.041	0.626	3
	T3	0.045	0.005	0.100	5
	T4	0.012	0.039	0.758	2
	T5	0.027	0.036	0.566	4
	T6	0.050	0.001	0.019	6
Autumn of 2018	T1	0.005	0.041	0.901	1
	T2	0.027	0.030	0.520	3
	T3	0.043	0.003	0.058	5
	T4	0.013	0.031	0.697	2
	T5	0.030	0.026	0.458	4
	T6	0.042	0.003	0.064	6

4 Discussion

Plant height, stem diameter, dry biomass distribution, and root-shoot ratio are important indexes to reflect crop growth as well as water and fertilizer supply conditions. According to the results of the present study, APRI technique is more beneficial to the formation of plant height, stem diameter, and dry biomass of tomatoes compared with FPRI and TSRI techniques in the application of biogas slurry and water together. The primary reason was that the root zone soil of tomatoes in APRI treatment constantly went through the dry-wet cycle, and the appropriate water stress and re-watering treatment made the compensation effect to plant more obvious[13] and thus promote plant growth. On the other hand, APRI could promote root growth, and increase root length and fibrous root density[29], which will make the irrigated water infiltrate in the horizontal direction more easily and finally maintain the nutrients in the plough layer of tomato for the nutrients of biogas slurry migrating with water together[30]. Therefore, compared with TSRI and FPRI treatments, APRI treatment could better promote the absorption and utilization of water and nutrients by plant roots, which provides better micro environments for tomato growth. Meanwhile, from the perspective of root-shoot ratio response, T1 treatment was more conducive to balancing the dry matter accumulation in the aboveground and underground parts of plant. This might be because a certain degree of water stress promotes the growth of roots, and the technique of applying water/biogas slurry with hole irrigation enable the water and fertilizer in the root zone distribute more evenly[8]. According to the distribution of root biomass in different soil depths, the root biomass in the top soil layer (0-15 cm) under surface irrigation treatments was larger in comparison to hole irrigation, whereas the application of water/biogas slurry together with hole irrigation could promote root growing into deeper soil (15-30 cm), which not only helps the crop growth, but also strengthens the plant stress resistance (resistance to drought, lodging, pests, diseases, etc.). This was mainly due to the better transportation of water and fertilizer to the crop root zone with the water/biogas slurry hole irrigation, which was more conducive to the absorption of water and fertilizer by the root system[8]. Moreover, it avoided the situation of a large amount of nutrient in the biogas slurry retained in the surface soil layer and resulted in inhibiting effects of the roots absorption due to the higher nutrient concentration in case of surface irrigation. At the same time, the water and fertilizer transported with hole irrigation could alleviate the water and nutrients shortages in the underlying soil around the crop root zone, balance the distribution of water and nutrients in the root zone, facilitate the downward growth of roots, and increase the surface area of tomato roots[11].

High-quality crop fruits are the synthesis and accumulation of high-efficiency photochemical products and plant healthy growth and metabolism. When certain measures are taken to promote the transfer of these assimilates to crop fruits and change the metabolic pathways, the goal of improving fruit quality can be achieved[31]. Under the same irrigation method (hole irrigation or surface irrigation), APRI had a strong positive effect on tomato yield and quality as well as WUE, and various indexes were significantly higher than those under TSRI and FPRI. This was mainly because APRI provides better water and nutrient supply for the crop root zone, which was more conducive to plant photosynthesis, increases the accumulation of assimilates[32] in crops and finally promotes the growth of tomato fruits. In addition, APRI technique could effectively promote the growth of tomato roots, and increase the root surface area and water use efficiency of plant[32]. Meanwhile, the moderate water stress under APRI induced the synthesis of Abscisic Acid (ABA) in plants[33]. And ABA could adjust leaf stomatal aperture, inhibit plant transpiration, balance water and fertilizer absorption and metabolism[34], and further improve fruit quality and water use efficiency. Under the same irrigation techniques (hole irrigation or surface irrigation), the water use efficiency and quality indexes of tomato yield treated by integrated water/biogas slurry hole irrigation were higher than those by surface irrigation. The primary reason was that compared with water/biogas slurry surface irrigation, hole irrigation could better promote root development, improve root surface area, facilitate the absorption of water and fertilizer, increase tomato yield and quality, and raise water use efficiency[35].

Comprehensive crop quality evaluation and comprehensive index evaluation are important basis for modern agricultural management (production, storage, transportation, and sales)[36]. The comprehensive quality of tomatoes is affected by multiple indicators, and it is difficult to use a single indicator to characterize the comprehensive quality of tomatoes, which is neither reasonable nor scientific. At the same time, different indicators have different degrees of influence on the comprehensive quality of tomato, so it is necessary to conduct a comprehensive evaluation based on relative importance, and principal component analysis (PCA) can just meet the dimensionality reduction evaluation under multi-indicator data, making the evaluation process simple and reliable[24,37]. In addition, The TOPSIS method is a multi-objective decision analysis method. By detecting the distance between the evaluation object and the optimal solution and the worst solution, a more real, intuitive, and reliable evaluation conclusion can be obtained. The comprehensive benefit of tomatoes is difficult to evaluate with a single index, but the sum of the interactions of multiple indexes such as growth status, yield, quality, and water use. Therefore, the TOPSIS method was used to evaluate the comprehensive benefit of tomatoes in order to obtain a more representative evaluation conclusion[38]. In general, some scholars have adopted PCA method and TOPSIS method to analyze the comprehensive quality and the comprehensive benefit of crops, which both achieved ideal results. In the present study, the principal component analysis (PCA) method was used to comprehensively evaluate the eight quality indicators of tomatoes under different treatments. The results showed that under the same irrigation method, APRI was more conducive to the overall quality of tomatoes, and the application of water/biogas slurry with hole irrigation could improve tomato quality when compared with surface irrigation. This is consistent with the relevant results obtained by Du et al.[39], Wang et al.[40], and by Zheng et al.[11]. TOPSIS method has been proven to be a good evaluation method in agricultural production[10]. The comprehensive index evaluation results of TOPSIS showed that T1 treatment had excellent performance in the multi-index evaluation system so can be used as an effective application combination for the implementation of integrated water/biogas slurry irrigation.

5 Conclusions

Different techniques in water/biogas slurry application have significant impacts on the growth, yield, and quality as well as water use efficiency of tomatoes. In terms of biogas slurry irrigation technique, APRI can enhance tomato plant growth, increase tomato yield, water use efficiency, and improve fruit quality and taste. As for biogas slurry irrigation method, hole irrigation is significantly better than surface irrigation in improving the growth, yield, fruit quality, and water use efficiency of tomato. Thus, the coupling of APRI and hole irrigation can effectively increase the yield, quality, and water use efficiency of tomato, and the results of PCA and TOPSIS proved it, both results of which showed that T1 treatment is the best combination of water/biogas slurry integrated irrigation.

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