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Full Length Article

Animal Based Biogas Digestate Application Frequency Effects on Growth and Water - Nitrogen use Efficiency in Tomato

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Abstract

Anaerobic digestion residues (digestate), has low nutrients concentration in nature and known as new type valuable organic fertilizers, that should be applied frequently to meet the plant growth. In present study, the performance of animal based biogas digestate frequencies (4 d, 6 d, 8 d) was evaluated and compared with conventional mineral fertilizer (CF) and no fertilizer (CK) in greenhouse during 2017 and 2018. The application of digestate and mineral fertilizer were mixed with water via two holes on both sides of plant. All treatments (digestate application frequencies is 4 d, 6 d, 8 d, CK and CF) were irrigated with similar method and the same amount of water. The plant height, stem diameter, biomass, yield, quality and water use efficiency (WUE) of tomato were measured, and the nitrogen content in each 10 cm soil layer and the nitrogen use efficiency (NUE) were assessed. The results showed that the growth, yield and tomato quality in 4 d and 6 d treatments were both superior than CF treatment, and the digestate application frequencies in 4 d and 6 d treatments can satisfy the demand of tomato growth. The 4 d digestate frequency had the highest total biomass, yield, fruit quality and WUE among all treatments, also had higher NUE, therefore, the digestate application frequency of 4 d was best and can be used as an appropriate option in digestate agricultural use under hole irrigation.

Keywords: Digestate; Frequency; Tomato quality; Yield; Water use efficiency; Nitrogen use efficiency

Introduction

Renewable energy has becoming the fastest growing source of energy, and the global has set the ambitious goal to provide 14% of world energy demand coming from renewable sources by 2040 compared to 4% in 2016 (BP, 2018). To reach this goal the use of all kinds of existing renewable energy need to grow fast. Anaerobic digestion of livestock and agricultural wastes is an established and robust method for bioenergy production and energy recovery (Abubaker *et al*., 2012). The main benefits of anaerobic digestion are biogas production and reduction in greenhouse gas emission. Together with biogas, anaerobic digestion produces large amounts of residual material (digestate), which need to be managed and utilized in appropriate ways to avoid any negative impact on environment and bioenergy development. The worldwide interest of digestate management was used as soil amendments or fertilizers to return nutrients back to the soil ecosystem. It is considered an appropriate way (Odlare *et al*., 2011; Alburquerque *et al*., 2012).

At the same time, long-term application of mineral fertilizer and surface irrigation in intensive agriculture has promoted soil degradation, organic and fertility loss, decreased the water and fertility use efficiency and finally reduced the yield and crop quality. The digestate, containing a variety of water-soluble nutrients required for crop growth, like nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and other essential amino acids and growth hormones, *etc*. (Insam *et al*., 2015; Hupfauf *et al*., 2016; Li *et al*., 2016). It has been documented that digestate application can increase the yield of rice, improve soil organic matter content and promote soil nitrogen content (Lu *et al*., 2012). Ding *et al.* (2017) indicated that the application of organic fertilizers can improve soil pH and the fungal community structure, and was in favor of crop growing well. Duan *et al.* (2011) showed that appropriate application of anaerobic digestion residues can improve the yield and quality of cucumber and reduce CO_2 emission in greenhouse. Previous researches (Kurchania and Panwar, 2011; Al-Juhaimi *et al*., 2014) also showed that there were no heavy metal elements contained in soil after the application of anaerobic fermentation slurry, and the application of digestate can improve the physical conditions of the soil and increase the growth and yield of wheat and the trace elements content in the leaves of alfalfa.

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Although, the digestate has been examined had lots of nutrients and elements needed for plants growth and can be used as fertilizers (Insam *et al*., 2015), the liquid digestate has the character of high water and low nutrients concentration, which cannot be used in drip irrigation system for small particles and high viscosity easily blocked the dropper. Now a days, the use of digestate was mainly in furrow irrigation and flood irrigation (Garg *et al*., 2005; Al-Juhaimi *et al*., 2014), which was not only a waste of digestate but also caused pollution to the environment. Studies (Shen *et al*., 2018) have shown that there was a potential risk of promoting secondary salinization of soil in the utilization of anaerobic fermentation slurry, and the researchers also proposed to control the amount of anaerobic fermentation slurry to prevent pollution to the soil environment. Therefore, a scientific and appropriate digestate application method is needed. Zheng *et al.* (2018) proposed that the liquid digestate can be used with water integrated *via* the hole irrigation method. This method had the benefits of conveying the mixture of digestate and water integrated to the crop root zone through two holes on both sides of the plant; reduced the waste of water and fertilizer. However, the application amount, concentration and use frequency of digestate and its effects on plant growth, yield and quality were still not clearly at present, and were urgent needed to be examined.

The main objective of the present study was to evaluate the digestate application frequency on tomato growth, yield, fruit quality and water and nitrogen use efficiency, and compare its performance with treatments applied with conventional mineral fertilizer and treatment with no fertilizer. To achieve this objective, two years greenhouse experiments were conducted in 2017 and 2018, and three digestate application frequencies of 4 d, 6 d and 8 d were evaluated.

Materials and Methods

Experimental Site and Materials

The experiments were conducted during July to November in 2017 and March to July in 2018 in a greenhouse, belonged to the Irrigation Experiment Center, Lanzhou University of Technology, Lanzhou, Northwest of China (36° 03′ N, 103° 40′ E). The region has a temperate semi-arid continental climate with a mean annual precipitation of 310.5 mm and evaporation of 1158.0 mm, and a mean annual temperature of 8.9℃. The soil type in the experimental field is silty loam, with silt 64.6%, clay 10.1% and sand 25.3%. The measured physical and chemical properties of the soil in the 0–60 cm depth were as follows: organic matter 8.6 and 8.35 $g{\cdot}kg^{-1}$, total nitrogen 1.07 and 1.03 $g{\cdot}kg^{-1}$, total phosphorus 1.54 and 1.25 $g{\cdot}kg^{-1}$, and total potassium 19.53 and 17.24 $g{\cdot}kg^{-1}$ in 2017 and 2018, respectively. The average soil bulk density in the 0–1.0 m soil layer is 1.40 g/cm^3, and the maximum water holding capacity is 25% (mass water content). The digestate applied in the experiment were directly collected from the biogas digesting tank of Holstein Breeding Dairy Breeding Center in Huazhuang, Lanzhou, which was the biogas residues based on cattle manure as raw materials. The anaerobic process was conducted at a temperature of 37ºC and the digestate was sampled and characterized after storing 2 months at a temperature of <4ºC to separate liquid from solid digestate. The liquid digestate was used in present study and the main characteristics of that were: organic matter 10.75 $g{\cdot}L^{-1}$, total nitrogen 2.43 $g{\cdot}L^{-1}$, total phosphorus 0.533 $g{\cdot}L^{-1}$ and total potassium 1.186 $g{\cdot}L^{-1}$.

Tomato (*Solanum lycopersicum* L., Zhongyan No.958 F1) seed was nursed on Jun. 22 and planted on Jul. 15, 2017 when the plants had four leaves. The experiment ended on Nov. 28, 2017. In 2018, the experiment was started on Mar. 12 and ended on Jul. 10. 2000 mL water was irrigated immediately after planting and the plastic film was covered 3 three days later. The same methods of pollination, cultivar, pest control and irrigated water amount were used for all the treatments.

Experimental Design

Treatments were three digestate application frequencies (4 d, 6 d and 8 d) and two control treatments (CK, CF), and each treatment were replicated three times, totally 15 treatments. Three digestate application frequencies include the digestate applied frequencies of 4 d, 6 d and 8 d, CK was treatment with no fertilizer application and CF was treatment applied with mineral fertilizer. The digestate was mixed with water together and irrigated via two holes on both sides of plants, and the volume concentration of digestate was 20%. The chemical fertilizer was also applied with hole irrigation method and the amount added were: nitrogen 78 $kg{\cdot}ha^{-1}$, phosphorus 94.5 $kg{\cdot}ha^{-1}$ and potassium 97.5 $kg{\cdot}ha^{-1}$, according to the experience of local farmers.

The ridge on which tomato was planted was 3.6 m (length) × 0.6 m (width) × 0.15 m (height), and the space between two ridges was 0.6 m between two plants was 0.3 m. 12 plants were planted on each ridge. Impervious geotextiles of 1.0 m in depth were set between two adjacent treatments to prevent the mutual infiltration influence of the water and fertilizer.

The water was irrigated every 2 days, and the amount of water was controlled during the entire growth period using an evaporation of the E601 evaporator placed in the greenhouse, which was determined by the following formula (Kirda, 2002):

$$M = K_p \times S \times E_p \quad (1)$$

where, M is the amount of irrigation water (mL), K_p is the coefficient of evaporation pan, here is 0.6; S is the evaporation area, 0.3×0.6 m; E_p is the amount of evaporation in two irrigation intervals (mm).

The growth period of tomato was divided into four stages: seeding stage, flowering and fruit-setting stage, fruit expanding stage, and fruit mature stage. The number of growing days and the amounts of water and digestate consumption in various treatments were shown in Fig. 1.

Sampling and Measurements

Plant height and stem diameter: To monitor the dynamic growing of tomato under various treatments, three plants were selected randomly at each treatment and the average value was taken as the plant height and stem diameter. The measurements were started 11 days after planting and were measured every 4 days. The plant height was measured using a tape measure from ground level to the highest stem tip, and the stem diameter was determined with a micrometer calipers at the base of the stem by the cross method.

Yield and total dry biomass: The fruit was harvested every 2–3 days during the mature period, the yields and numbers of fruits of each plant were recorded at the time of picking.

Dry biomass content: The roots, stems, leaves and fruits are bagged separately immediate after sampling at the end of each growing period, and dried in an oven at 105°C for 15 minutes, then the oven temperature was set to 75°C to dry the sample to constant. Then, the dry biomass was weighed by an electronic balance (precision is 0.01 g). The total dry biomass content of the entire plant was the sum of all parts biomass of the plant.

Soil nutrient contents: Four soil samples were randomLy collected from the sites of each treatment before planting and at each growing period. The soil was sampled every 10 cm in layer and to the depth of 60 cm. The soil samples were air-dried and sifted through a 0.2 mm sieve before measurements. The average soil nutrient contents were the average value of the four samples in each layer.

Digestate properties determination: The total nitrogen was determined by the Kjeldahl method; nitrate nitrogen was determined by ultraviolet spectrophotometer method; ammonium nitrogen was determined by the Na's reagent colorimetric method; pH was measured by glass electrode method; dry matter quality was determined by the drying and weighing method; electrical conductivity was measured using an electrical conductivity meter; viscosity was determined using an Ostwald viscometer. The properties of the digestate were determined once a month.

Tomato quality determination: The fresh fruit quality was measured after the first fruit was ripened. Vitamin C (Vc) content was determined by the molybdenum blue colorimetric method; soluble protein was determined by the Coomassie brilliant blue G-250 staining method; soluble total sugar was determined by the anthrone method; organic acid content was determined by the titration method; soluble solid content was determined by the WAY-2S Abbe refractometer.

Water use Efficiency and Nitrogen Use Efficiency

The water use efficiency (WUE) and nitrogen use efficiency (NUE) were calculated as follows:

$$WUE = \frac{Y}{W} \qquad (2)$$

$$NUE = \frac{N_p}{N_a + N_d} \times 100\% \qquad (3)$$

Where, Y is fruit yield of tomato, kg; W is water consumption, m^3; N_p is the nitrogen absorbed by plant, kg; N_a is the nitrogen applied in soil, kg; N_d is the nitrogen decreased in soil during the entire growing period, kg.

Data Analysis

Data statistical analysis and plotting were performed with SPSS 24.0 and Origin 9.0. One-way analysis of variance (ANOVA) and least significant difference (LSD, 5% level) pairwise comparisons were performed to determine the significant differences among treatments.

Results

Tomato Growth

The measurements of plant height (Fig. 2) and stem diameter (Fig. 3) were started 11 days after planting and measured every 4 days. The plant height in various treatments presented the trend of 4 d>6 d>CF>8 d>CK in 2017 and the trend of 4 d>6 d>8 d>CF>CK in 2018. The plant height in 4d treatment was higher than in other treatments, and in CK was the smallest. Compared to CK, the plant height in 4 d, 6 d, and 8 d treatments increased by 23.44, 19.67 and 12.97%, and increased by 12.00, 6.00 and -3.40% in comparison with CF in 2017. In 2018, the plant height in 8d treatment was a little higher than in CF, increased by 1.00%. For the stem diameter, the trends of 4 d>6 d>CF>8 d>CK in both two season experiments was observed. The stem diameter in 4 d, 6 d, and 8 d treatments increased by 12.52, 10.65 and 3.55% in comparison with CK, and that increased 0.80, 0.51 and -0.48% when compared with CF in 2018.

In general, appropriate digestate application was conducive to plant growth, which was both increased the plant height and stem diameter of tomato. 4 d and 6 d treatments were much better than CF treatment in promoting plant growth, and 8 d treatment was a little inferior to it.

Dry Biomass Accumulation

The total dry biomass showed a significant response ($P < 0.05$) to various digestate application treatments, in which 4d treatment yielded the most accumulation of plant dry matter, followed by 6 d and CF treatments, and CK yielded

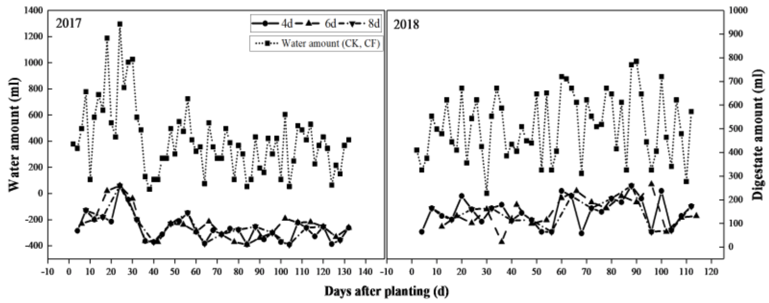

Fig. 1: The irrigation and digestate application process in experiments during 2017 and 2018. Three digestate frequencies: 4 d, 6 d and 8 d, chemical fertilizer (CF), no fertilizer (CK)

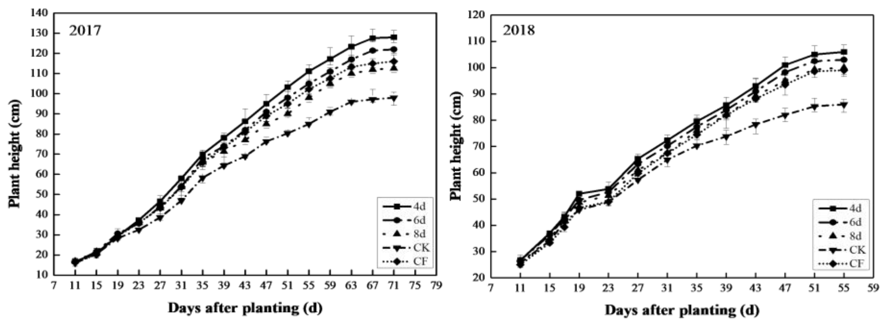

Fig. 2: Plant height of tomato under various treatments in 2017 and 2018. Three digestate frequencies: 4 d, 6 d and 8 d. Chemical fertilizer (CF). No fertilizer (CK). Vertical bars indicate standard error of the mean at $P < 0.05$

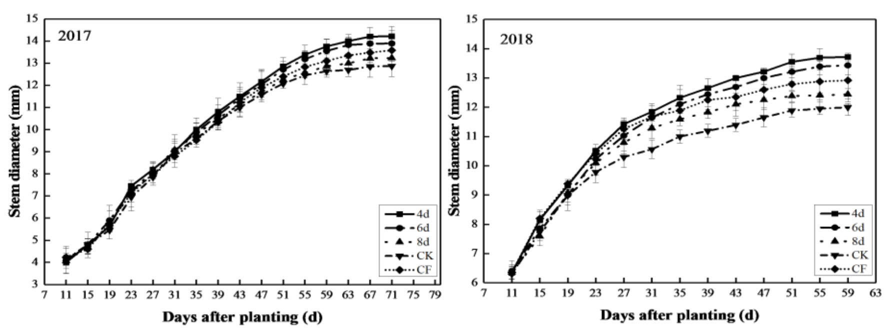

Fig. 3: Stem diameter of tomato under various treatments in 2017 and 2018. Three digestate frequencies: 4 d, 6 d and 8 d. Chemical fertilizer (CF). No fertilizer (CK). Vertical bars indicate standard error of the mean at $P < 0.05$

the lowest of it (Fig. 4). Significant differences ($P < 0.05$) in total plant dry biomass were observed among all treatment except for that between 6d and CF treatments. Compared with CK, the total plant dry biomass of 4 d, 6 d and 8 d treatments increase by 62, 46 and 32% in 2017, and 165, 126 and 88% in 2018. Compared with CF, the total plant dry biomass of 4 d, 6 d and 8 d treatments increased by 9.02, -0.46 and -11.48% in 2017, 24.56, 6.53 and -11.51% in 2018.

The fruit biomass accounted for a large part of the total plant biomass, followed by stem, leaf and root biomass (Fig. 4). The fruit biomass presented no significant differences among 4 d, 6 d and CF treatments ($P < 0.05$), but the differences were significant among them and 8 d, CK treatments in 2017. In the experiment of 2018, significant differences in fruit biomass were also observed among all treatments except for between 6 d and CF treatments. For the biomass accumulation in stem, leaf and root, significant differences were yielded between 4 d and other treatments, while no significant differences were observed among treatments of 6 d, 8 d, CF and CK, and no differences between 8 d and CF treatments. The results illustrated that appropriate digestate application was not only increasing the yield of tomato, but also promoting the plant growing vigorously.

Table 1: Yield, water irrigation, water consumption and WUE under various treatments

Year	Treatment	Yield ($kg\cdot hm^{-2}$)	Irrigation water ($m^3\cdot hm^{-2}$)	Water consumption ($m^3\cdot hm^{-2}$)	WUE ($kg\cdot m^{-3}$)
2017	4d	282759.26a	1713.39	1916.70b	147.52a
	6d	266425.93b	1713.39	1890.73b	140.97b
	8d	236018.52c	1713.39	1840.85b	128.21c
	CK	171555.56d	1713.39	2455.23a	69.87d
	CF	266481.67b	1713.39	1901.91b	140.11b
2018	4d	277430.04a	2392.89	2712.46a	102.28a
	6d	245056.17b	2392.89	2576.83b	95.10b
	8d	172900.00d	2392.89	1920.99c	90.01c
	CK	72262.18e	2392.89	2064.63c	35.00d
	CF	215335.27c	2392.89	2509.59b	85.81c

Three digestate frequencies: 4 d, 6 d and 8 d. Chemical fertilizer (CF). No fertilizer (CK). Letters indicate significantly differences at $P < 0.05$ among treatments

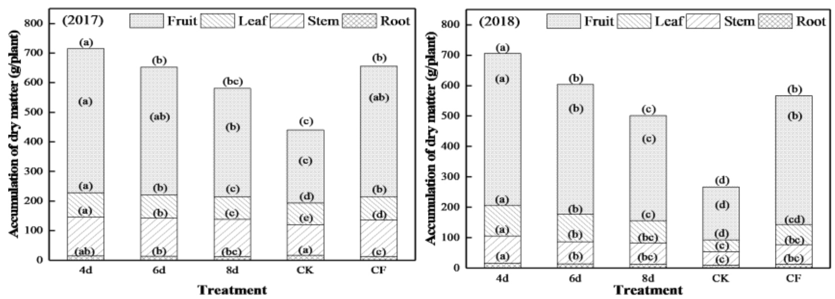

Fig. 4: Effect of digestate application on crop dry biomass accumulation in various parts of tomato. Three digestate frequencies: 4 d, 6 d and 8 d. Chemical fertilizer (CF). No fertilizer (CK). In each column Letters indicate significantly differences at $P < 0.05$ among treatments

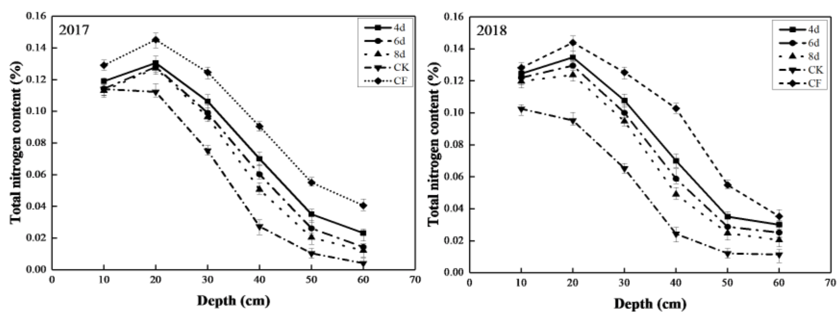

Fig. 5: Total nitrogen content in soil layer 0-60 cm after tomato harvested under various treatments. Three digestate frequencies: 4 d, 6 d and 8 d. Chemical fertilizer (CF). No fertilizer (CK). Vertical bars indicate standard error of the mean at $P < 0.05$

Tomato Yield and Water Use Efficiency (WUE)

The yield and water use efficiency (WUE) of various treatments resulting in ANOVA analysis shown in Table 1 illustrated that the yields in two seasons showed the trends of 4 d>6 d>CF>8 d>CK, and significant differences can be observed among all treatments except between 6 d and CF. In 2017, when compared with CK, the yield of 4 d, 6 d and 8 d treatments increased by 39.33, 35.61, 27.31, and increased by 5.76, 0.22 and -12.91% in comparison with CF. In 2018, the yield of 4 d and 6 d treatments increased by 73.95, 22.38 and 70.51%, and 12.13% in comparison with CK and CF, respectively.

The crop water use efficiency (WUE) was calculated in Table 1, which illustrated the trend of 4 d>6 d>CF >8 d>CK in the two seasons. There were significant differences can be observed in all treatments except that between 6d and CF treatments in 2017, 8 d and CF treatments in 2018. 4 d treatment obtained the highest WUE, which was 116% and 61% when compared with CK in 2017 and 2018, respectively. When compared with CF, the WUE of 4 d treatment increased by 5.3 and 19.2% in 2017 and 2018. The WUE decreased with the decrease of digestate application frequency, when compared with 4 d treatment, the WUE of 8 d treatment decreased about 13.1% and 12.0% in 2017 and 2018, respectively. The results showed that the application of digestate can increase the efficiency of water use, and appropriate digestate application frequency can even increase the WUE up to 116% and 19.2% when compared to no fertilizer and chemical fertilizer treatments, finally improve the yield and water-saving.

Soil Total Nitrogen use

The total nitrogen (N) contents (Fig. 5) in soil layer of 0–60 cm in 2017 and 2018 showed that the variation of N content in all treatments presented similar trends from 0 to 60 cm, and the N content decreased with the increase of digestate application intervals, which showed the trends of CF>4 d>6 d>8 d>CK. The N content was much higher in the depth of 0–40 cm with a peak value in the soil layer of 10–20 cm, and the N content in soil layer 0–40 cm takes up more than 80% N nutrients in soil and which was the range of tomato roots growing and much easier for crop utilization.

Compared with CK, the average N content in 4d, 6d and 8d treatments increase by 41.02, 28.75 and 22.25% in 2017, and 61.54, 49.38 and 39.10% in 2018. CF treatment had the highest N content in all treatments and the N content in 4d, 6d and 8d treatments decreased about 17.25, 24.45 and 28.26% in 2017 and that decreased 14.97, 21.4 and 26.79% in 2018 when compared to CF. The results showed that N content in digestate application treatments cannot as much as the CF treatment, maybe the digestate frequency was small and a much higher frequency was needed. However, too much N accumulation can lead to the surplus of nitrogen, so the use efficiency and its influences on yield and fruit quality need took into account.

The nitrogen use efficiency (NUE) of treatments with fertilizer and various digestate application frequencies illustrated that the NUE in digatate application treatments were much higher than fertilizer, and for 6 d treatment was the highest in both two season experiments (Fig. 6). In comparison with CF, the NUE in 4 d, 6 d and 8 d treatments increased by 34.44, 46.37 and 28.99% in 2017, and increased by 22.73, 33.22 and 18.18% in 2018. The results showed that digestate addition can effectively promote the nitrogen utilization efficiency in plants. Meanwhile, the NUE in the experiment of 2017 was a little higher than in 2018, which indicated that the NUE was influenced by the environmental factors and planting time.

Tomato Quality

Impact of digestate application frequency and chemical fertilizer treatment on tomato fruit quality indices, including organic acid, soluble sugar, sugar/acid ratio, vitamin C (Vc), soluble protein, soluble solids content and firmness, analyzed with ANOVA models (Table 2). Significant differences ($P < 0.05$) in fruit quality indices except soluble solids and firmness can be seen among treatments of CK, CF and digestate application treatments. In present study, the soluble sugar and sugar/acid ratio increased with the increase of digestate application frequency with following trend of CK<CF<8 d<6 d<4 d, while the organic acid showed the adverse trends. The soluble sugar content, organic acid content and sugar/acid ratio can be considered as the eating quality, which determines the taste of tomato. When compared to CK, the sugar/acid ratio in 4 d, 6 d and 8 d treatments increased by 128, 85 and 59% in 2017 while 75, 47 and 31% in 2018, when compared to CF, increased by 11, 75 and 50% in 2017, 66, 40 and 24% in 2018. Four day treatment also got the highest Vc and soluble protein contents among all treatments, followed by 6 d, 8 d, CF and CK treatments. The Vc and soluble protein contents in 4 d treatment increased by 50 and 55% in comparison with CK, and that increased by 43 and 48% compared to CF in 2017, 25 and 65% in comparison with CK, 21 and 54% compared to CF in 2018, respectively. Also, 4 d treatment had the highest soluble solids content and firmness, next by CF treatment, CK had the lowest value of them, and the differences were notably. The results indicated that tomato in appropriate digestate application frequency treatment can obtain a desirable quality, which was much better that CF and CK treatment.

Discussion

Water and fertilizer are key factors in plant growing and biomass accumulating, and the biomass was the basis of crop yield formation. Kouřimská *et al.* (2012) indicated that liquid digestate can be used as a high quality organic fertilizer, in which the nutrients were more conductive to plant absorb and utilize, and finally improve the yield of crop. Meanwhile, digestate addition can improve the soil structure and physical properties, provide good conditions for plant growing (Garg *et al*., 2005; Kurchania and Panwar, 2011; Muhammad *et al.*, 2018). In present study, the total biomass accumulation of tomato increased with the increase of digestate application frequency, and 4 d treatment had the highest of it, followed by 6 d and CF treatments, next by 8 d treatment, and CK treatment had the lowest biomass. The results showed that the frequencies of digestate application in 4 d and 6 d treatments can supply enough nutrients for plant growing. The total biomass and yield obtained in 2017 were much higher than in the similar treatment in 2018, which may be due to the environmental factors in greenhouse, for the experiment in 2018 was carried out in spring and summer, the temperature and humidity were much higher than 2017. High temperature and humidity can exert an inhibiting effect on plant growing (Bharti and Khurana, 1997; Grace *et al.,* 2010; Chen *et al.*, 2018) by reducing the assimilative capacity of CO_2 (Meng *et al.*, 1999), at last influence the formation of total biomass.

Water use efficiency (WUE) is one of the important contents of agricultural research in arid and semi-arid areas, and improve of which is the main goal of agricultural production (Hipólito *et al.*, 2015). According to equation (2), the ratio of yield to water consumption is used to calculate the WUE of tomato. In present study, 4 d treatment

Table 2: Effect of digestate application frequency on fruit quality index of tomato

Year	Treatment	Organic acid (%)	Soluble sugar (%)	Sugar/acid ratio	Vc (mg·100 g^{-1})	Soluble protein (mg·g^{-1})	Soluble solids (%)	Firmness (%)
2017	4d	0.72b	2.98a	4.13a	43.95a	0.68a	5.70a	5.69a
	6d	0.85b	2.85a	3.35a	38.04b	0.52ab	5.36c	5.48c
	8d	0.94ab	2.70a	2.87ab	35.70b	0.50ab	5.20d	5.61b
	CK	1.16a	2.10b	1.81b	29.34c	0.44b	5.18d	5.42c
	CF	1.19a	2.28b	1.92b	30.85c	0.46b	5.45b	5.45c
2018	4d	3.02b	3.10a	1.03a	48.76a	0.43a	6.75a	7.09a
	6d	3.39ab	2.95a	0.87ab	42.73ab	0.39a	6.50b	6.57c
	8d	3.62ab	2.79a	0.77ab	42.06ab	0.30ab	6.00d	6.00d
	CK	3.75a	2.21b	0.59b	39.05b	0.26b	6.13c	6.02d
	CF	3.82a	2.35b	0.62b	40.39b	0.28b	6.50b	6.76b

Three digestate frequencies: 4 d, 6 d and 8 d. Chemical fertilizer (CF). No fertilizer (CK). Letters indicate significantly differences at P<0.05 among treatments

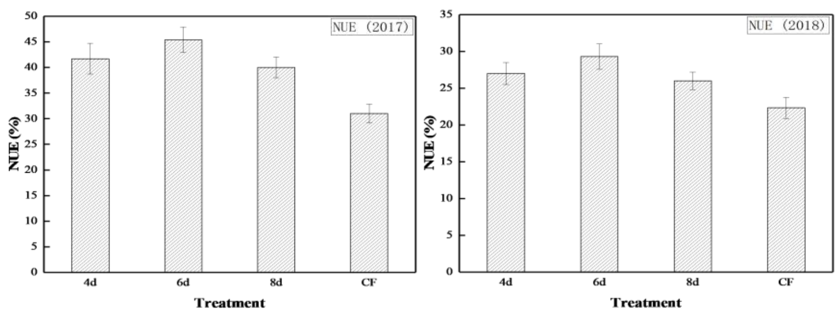

Fig. 6: Influence of digestate application frequency on total nitrogen use efficiency (NUE) of tomato. Three digestate frequencies: 4 d, 6 d and 8 d. Chemical fertilizer (CF). No fertilizer (CK). Vertical bars indicate standard error of the mean at $P < 0.05$

obtained the highest yield both in the experiment of 2017 and 2018, the water consumption of which ranked second in 2017 and first in 2018 among all treatments, and thus a highest WUE received in this treatment. The results indicated that the irrigation frequency of 4 d have significant advantages in crop yield formation. And we all know that the formation of crop yield depends on water and nutrients supply and the absorption of crop roots (Yaghi *et al*., 2013). Ladha *et al.* (2004) pointed out that the increase of crop yield and WUE can be realized by regulating the water and fertilizer utilization mode. In this experiment, the irrigation water amount and digestate concentration are similar in all treatments, and the difference of yield and WUE among all treatments resulting from the irrigation frequencies. Therefore, the irrigation frequency of 4 d can supply efficient water and nutrient for crop growth, and finally get a supreme yield and WUE. Meanwhile, digestate contains a variety of water-soluble nutrients, such as nitrogen, phosphorus, potassium, calcium, magnesium, *etc*., as well as some essential amino acids, vitamins and growth hormones, needed for crop growth, which promote the water and nutrients absorption for plant, and thus play a positive role in improving crop yield and water use efficiency (Tambone *et al*., 2010; Ledda *et al*., 2013; Oh *et al*., 2014).

Appropriate digestate addition can improve soil aggregates structure, physical and chemical properties, and enhance the soil fertility (Nkoa, 2014). Peu *et al.* (2007) indicated that digestate application can increase the soil N content by inducing N immobilization in soil. Matsunaka *et al.* (2006) showed that the digestate applied in early spring can not only increase the NUE of grassland, but also increase the yield of forage grass. In present study, the CF treatment had the highest N content both in the experiments of 2017 and 2018, while its NUE was the lowest among all treatments. However, 4 d, 6 d and 8 d treatments had lower N content and superior NUE, which increased in 4d, 6d and 8d treatments by 34.44, 46.37 and 28.99% when compared to CF treatment. The results indicated that digestate as a multielement organic fertilizer was beneficial to crop utilization, while chemical fertilizer application can easily cause the N accumulation in soil, and sometimes lead to soil acidification after long-term use. Meanwhile, the N content in the soil layer 0–40 cm accounted for 89 and 80% during both years and tomato roots were most distributed in soil layer of 0–50 cm (Nefzi *et al*., 2017), which indicated that the hole irrigation method used in present study was conductive to N accumulated in crop root zone and was easily for crop absorption and utilization, consequently increased the NUE of tomato.

Digestate application can improve the soluble sugar, organic acid, Vc content, firmness and eating quality of tomato, and decrease the nitrate content in fruit (Sui *et al*., 2016). In present study, the soluble sugar, Vc content, soluble protein and sugar/acid ratio were increased with the increase of digestate application frequency, while the organic acid presented the adverse trends. Yue *et al.* (2003) considered that the taste of tomato depends on the absolute contents of soluble sugar and organic acid. The present experiments results indicated that digestate application can increase the soluble sugar content in tomato, and decrease the organic acid content, thus increase the sugar/acid ratio and make the tomato taste delicious. The superior tomato quality in digestate treatments may be due to the rich multi-nutrients like nitrogen (N), phosphorus (P), potassium (K) and magnesium (Mg), amino acid and other growth hormones in digestate (Alburquerque *et al*., 2012). 4 d treatment had the best fruit quality in all treatments and which indicated the digestate application frequency of 4 d was positive in plant utilizing all kinds of nutrients and consequently obtained high tomato quality.

Conclusion

It is concluded that d treatment obtained the highest total biomass, yield and water use efficiency among all treatments. Compared with traditional fertilizer treatment (CF), the total biomass, yield and water use efficiency of 4 d treatment increased by 9.02, 5.76 and 5.30% in 2017, 24.56, 22.38 and 19.20% in 2018, respectively. The content of Vc, soluble protein and sugar/acid ratio of 4d treatment increased by 43, 48 and 115% in 2017, 21, 54 and 66.4% in 2018 in comparison with fertilizer treatment (CF), respectively. The irrigation frequency of 4 d treatment can be used the best option for tomato cultivation in greenhouse.

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References

Abubaker, J., K. Risberg and M. Pell, 2012. Biogas residues as fertilisers - effects on wheat growth and soil microbial activities. *Appl. Energ.,* 99: 126–134

Alburquerque, J.A., C.D.L. Fuente, M. Campoy, L. Carrasco, I. Nájera, C. Baixauli, F. Caravaca, A. Roldán, J. Cegarra and M.P. Bernal, 2012. Agricultural use of digestate for horticultural crop production and improvement of soil properties. *Eur. J. Agron*., 43: 119–128

Al-Juhaimi, F.Y., S.H. Hamad, I.S. Al-Ahaideb, M.M. Al-Otaibi and M.M. El-Garawany, 2014. Effects of fertilization with liquid extracts of biogas residues on the growth and forage yield of alfalfa (*Medicago sativa* L.) under arid zone conditions. *Pak. J. Bot*., 46: 471–475

Bharti, A. and J.P. Khurana, 1997. Mutant of *Arabidopsis* as tools to understand the regulation of phenylpropanoids pathway and UVB protection mechanism. *Photochem. Photobiol*., 65: 765–776

BP energy outlook, 2018. *BP Energy Economics*. https://www.bp.com/energyoutlook

Chen, Q., S. Peng, H. Dong, W. Wang and L. Nie, 2018. Optimal nitrogen fertilizer management for direct seeding rice: A review. *Intl. J. Agric. Biol*., 20: 1382–1390

Ding, J., X. Jiang, D. Guan, B. Zhao, M. Ma, B. Zhou, F. Cao, X. Yang, L. Li and J. Li, 2017. Influence of inorganic fertilizer and organic manure application on fungal communities in a long-term field experiment of chinese mollisols. *Appl. Soil Ecol*., 111: 114–122

Duan, N., C. Lin, R.Y. Gao, Y. Wang, J.H. Wang and J. Hou, 2011. Ecological and economic analysis of planting greenhouse cucumbers with anaerobic fermentation residues. *Proc. Environ. Sci.*, 5: 71–76

Garg, R.N., H. Pathak, D.K. Das and R.K. Tomar, 2005. Use of fly ash and biogas slurry for improving wheat yield and physical properties of soil. *Environ. Monit. Assess.*, 107: 1–9

Grace, S.C., B.A. Logan and W.W. Adams, 2010. Seasonal differences in foliar content of chlorogenic acid, a phenylpropanoid antioxidant, in *Mahonia repens*. *Plant Cell Environ.*, 21: 513–521

HipólitoMedrano, M.Tomás, S. Martorell, J. Flexas, E. Hernández, J. Rosselló, A. Pou, J.M. Escalona and J. Bota. 2015. From leaf to whole-plant water use efficiency (WUE) in complex canopies: Limitations of leaf WUE as a selection target. *Crop J.,* 3: 220–228

Hupfauf, S., S. Bachmann, M.F.D. Juárez, H. Insam and B. Eichler-Löbermann, 2016. Biogas digestates affect crop P uptake and soil microbial community composition. *Sci. Total Environ.*, 542: 1144–1154

Insam, H., M. Gómez-Brandón and J. Ascher, 2015. Manure-based biogas fermentation residues - friend or foe of soil fertility? *Soil Biol. Biochem.*, 84: 1–14

Kirda, C., 2002. Deficit irrigation scheduling based on plant growth stages showing water stress tolerance. *Water Rep.*, 22: 3–10

Kouřimská, L., I. Poustková and L. Babička, 2012. The use of digestate as a replacement of mineral fertilizers for vegetables growing. *Sci. Agric. Bohem.,* 43: 121–126

Kurchania, A.K. and N.L. Panwar, 2011. Experimental investigation of an applicator of liquid slurry, from biogas production, for crop production. *Environ. Technol.*, 32: 873–878

Ladha, J.K., C.S. Khind, R.K. Gupta, O.P. Meelu and E. Pasuquin, 2004. Long-term effects of organic inputs on yield and soil fertility in a rice-wheat rotation. *Soil Sci. Soc. Amer. J*., 68: 845–853

Ledda, C., A. Schievano, S. Salati and F. Adani, 2013. Nitrogen and water recovery from animal slurries by a new integrated ultrafiltration, reverse osmosis and cold stripping process: a case study. *Water Res*., 47: 6157–6166

Li, X., J. Guo, R. Dong, B.K. Ahring and W. Zhang, 2016. Properties of plant nutrient: comparison of two nutrient recovery techniques using liquid fraction of digestate from anaerobic digester treating pig manure. *Sci. Total Environ.*, 544: 774–781

Lu, J., L. Jiang, D. Chen, K. Toyota, P.J. Strong, H. Wang and T. Hirasawa, 2012. Decontamination of anaerobically digested slurry in a paddy field ecosystem in Jiaxing region of China. *Agric. Ecosyst. Environ*., 146: 13–22

Matsunaka, T., T. Sawamoto, H. Ishimura, K. Takakura and A. Takekawa, 2006. Efficient use of digested cattle slurry from biogas plant with respect to nitrogen recycling in grassland. *Intl. Congr. Ser.*, 1293: 242–252

Meng, Q.W., E. Weis, Q. Zou and S.J. Zhao, 1999. Photoinhibition and photoprotection in ginkgo biloba leaves: influence of temperature, CO_2 and O_2. *Acta Bot. Sin*., 41: 398–404

Muhammad, I., F.U. Khan, A. Khan and J. Wang, 2018. Soil fertility in response to urea and farmyard manure incorporation under different tillage systems in Peshawar, Pakistan. *Intl. J. Agric. Biol*., 20: 1539–1547

Nefzi, A., H. Jabnoun-Khiareddine, R.A.B. Abdallah, N. Ammar, S. Medimagh-Saïdana, R. Haouala and M. Daami-Remadi, 2017. Suppressing fusarium crown and root rot infections and enhancing the growth of tomato plants by *Lycium arabicum* schweinf. ex boiss. extracts. *S. Afr. J. Bot.*, 113: 288–299

Nkoa, R., 2014. Agricultural benefits and environmental risks of soil fertilization with anaerobic digestates: a review. *Agron. Sustain. Dev.*, 34: 473–492

Odlare, M., V. Arthurson, M. Pell, K. Svensson, E. Nehrenheim and J. Abubaker, 2011. Land application of organic waste - effects on the soil ecosystem. *Appl. Energ.*, 88: 2210–2218

Oh, T.K., Y. Shinogi, S.J. Lee and B. Choi, 2014. Utilization of biochar impregnated with anaerobically digested slurry as slow-release fertilizer. *J. Plant Nutr. Soil Sci*., 177: 97–103

Peu, P., F. Birgand and J. Martinez, 2007. Long term fate of slurry derived nitrogen in soil: a case study with a macro-lysimeter experiment having received high loads of pig slurry (solepur). *Bioresour. Technol.*, 98: 3228–3234

Shen, Y., B. Ye and R.H. Lu, 2018. Potential effects of biogas slurry and biogas residues resource utilization on the secondary salinization of soil. *Hans J. Soil Sci.*, 6: 22–26

Sui, H.L., X.F. Chen, Qin, G.H.N. Wang, K.M. Xu and P. Ai, 2016. Effects of drip irrigation with biogas slurry on yield and quality of tomato and physical and chemical properties of soil. *Shand. Agric. Sci*., 48: 80–84

Tambone, F., B. Scaglia, G. D'Imporzano, A. Schievano, V. Orzi, S. Salati and F. Adani, 2010. Assessing amendment and fertilizing properties of digestates from anaerobic digestion through a comparative study with digested sludge and compost. *Chemosphere*, 81: 577–583

Yaghi, T., A. Arslan and F. Naoum, 2013. Cucumber (*Cucumis sativus* L.) water use efficiency (WUE) under plastic mulch and drip irrigation. *Agric. Water Manage.*, 128: 149–157

Yue, S.J., H.C. Liu and Y.F. Zhai, 2003. Studies on flavor of cherry tomato fruit. *Chin. Veg*., 3: 15–17

Zheng, J., E.J. Zhang, Y. Wang and X.Y. Wang, 2018. Analysis on the transport characteristics of water-biogas slurry integrated infiltration. *J. Lanzhou Univ. Technol*., 44: 58–64

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