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ORIGINAL RESEARCH ARTICLE

Effects of irrigation methods on transpiration and water use efficiency of tomato

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ABSTRACT

Objective: To explore the effect of high-frequency drip irrigation on the physiological water savings of facility tomatoes. Methods: A pot experiment was conducted to study the effects and mechanisms of conventional flood irrigation (CFI) and high-frequency drip irrigation (HDI) on the transpiration and water use efficiency of tomatoes. Results: a. During the whole growth period, the irrigation times of high-frequency drip irrigation were 44 times, which was 3.4 times of traditional flood irrigation, and the irrigation amount was only 71.0% of flood irrigation. However, there was no significant difference in fruit, stem, or leaf dry weight between the two treatments ($p > 0.05$). b. The average transpiration of tomatoes under high-frequency drip irrigation was 28.95 L/plant, which was significantly lower than that under traditional flood irrigation by 24.6%. c. Compared with conventional flood irrigation, high-frequency drip irrigation treatment significantly increased irrigation water use efficiency (biomass/irrigation volume) and water physiological use efficiency (biomass/transpiration volume) by 21.2% and 14.2%, respectively ($p < 0.05$). d. Compared with conventional flood irrigation, high-frequency drip irrigation significantly decreased tomato leaf area, stomatal conductance, and transpiration rate by 32.6%, 69.8%, and 54.3%, respectively, and significantly increased leaf $\delta^{13}C$ value ($p < 0.05$). Conclusion: High-frequency drip irrigation can not only reduce the amount of irrigation, and improve the utilization efficiency of irrigation water, but also put the plant in a certain state of water deficit, reduce leaf area, stomatal conductance, and transpiration rate, and then significantly reduce transpiration water consumption, improve the physiological water use efficiency of tomatoes, and realize physiological water savings.

Keywords: facility tomato; irrigation mode; transpiration consumes water; water use efficiency; stomatal conductance

1. Introduction

China is one of the countries with water resource shortages in the world, and the spatial distribution of water resources is not uniform. In 2019, the amount of water resources in our country is only 20.5% of the total water resources, while the cultivated land area is 52.8% of the cultivated land area[1]. The contradiction between supply and demand for water resources is the main factor restricting agricultural production in northern China. Therefore, the efficient use of agricultural water resources is of great significance to our northern agricultural production. Facilities vegetable is one of the most characteristic agricultural industries in

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the north of our country, with a growing area of more than 70%[2]. Among them, tomato is one of the main vegetable varieties planted in the facility, which has the characteristics of high production intensity, high yield, and high water demand. In facility tomato production, flood irrigation is still the main irrigation method[3–4], resulting in the waste of water resources and the large amount of water needed for nitrogen, resulting in the phenomenon of "luxury transpiration", resulting in the loss of ineffective quantity[5–6]. Therefore, it is imperative to improve the water use efficiency of the facility.

[Research Progress] Compared with traditional flood irrigation, the application of water-saving irrigation measures can significantly reduce the irrigation amount and improve the utilization efficiency of irrigation water[7–9]. Nie et al.[10] found in their research on tomato facilities in Shouguang, Shandong Province, that compared with traditional flood irrigation, drip irrigation could achieve 36% water savings, an 11.3% increase in production, and a 74% increase in irrigation water utilization efficiency. The research results of tomato facilities in Tianjin Wuqing also show that drip irrigation and fertilization can save irrigation water by about 40% compared with traditional flood irrigation without affecting tomato yield, thus significantly improving the utilization efficiency of irrigation water[11].

Only a small part of the water absorbed by plant roots is used for plant body construction, and the remaining 97%–99.5% is discharged from the body through transpiration[12]. Transpiration not only contributes to the absorption and transport of water and mineral nutrients (such as Ca^{2+} and Mg^{2+}) by plants[13–14], but also contributes to the maintenance of normal body temperature[15]. However, when the water consumption of plant transpiration exceeds the water required for physiological processes such as nutrient transport, photosynthesis, and crop growth, the phenomenon of "luxury transpiration" will occur[16], resulting in ineffective water loss and reduced water use efficiency. Therefore, reducing the luxury transpiration of plants can achieve physiological water savings and is also one of the most effective ways to improve the water use efficiency of crops and realize the efficient use of agricultural water resources[17]. Luxury transpiration is common in winter wheat in the North China Plain, which is closely related to soil water content. That is, luxury transpiration increases with the increase in soil water content. By reducing irrigation, the luxury transpiration of wheat can be reduced, and physiological water savings can be achieved[12].

[Entry point] At present, studies on water consumption and crop transpiration mainly focus on open-field crops[12,18–20], while studies on facility vegetables are few. Compared with field crops, vegetable production in facilities is in a closed or semi-closed state all year round, with its unique microclimate characteristics. The crop growth process cannot receive rainfall, and the dynamic change in soil moisture content depends on the frequency and quantity of irrigation[21], which may have an impact on transpiration and water consumption. Previous studies on the WUE of tomatoes in facilities mainly evaluated it from the perspective of yield, that is, the yield obtained per unit of irrigation[22]. However, there are few reports on the effects and mechanisms of different irrigation methods on transpiration consumption and water physiological use efficiency (biomass/transpiration) in tomato facilities. [Key issues to be solved] In this study, traditional flood irrigation and high-frequency drip irrigation were set up to study the effects and mechanisms of different irrigation methods on transpiration water consumption and water use efficiency of facility tomatoes, aiming to explore water-saving ways from the perspective of plant physiology and provide theoretical and technical support for the efficient utilization of water resources in facility tomatoes.

2. Materials and methods

2.1. Experimental design and management

The tested soil was obtained from vegetable greenhouses in Zhaili Village, Luocheng Street, Shouguang City, Shandong Province. Built in 2010, the greenhouses grow one crop of chilies a year. The 0–30 cm topsoil was collected, passed through a 5 mm sieve, and thoroughly mixed as soil for pot experiment. The soil texture is silty loam, and the basic physical and chemical properties are shown in **Table 1**. The tomato variety tested was "100fan–5" with a seedling age of 40 days.

Table 1. Basic physical and chemical properties of the tested soil.

Organic carbon/(g·kg^{-1})	Alkaline hydrolysis nitrogen/(mg·kg^{-1})	Available phosphorus/(mg·kg^{-1})	Available potassium/(mg·kg^{-1})	pH value	*EC*/(μS·cm^{-1})
28.6 ± 2.1	191 ± 13	597 ± 40	877 ± 13	7.4 ± 0.1	298 ± 0.9

The pot experiment was conducted in the solar greenhouse of Qingdao Agricultural University from 26 March to 15 June 2021. During the experiment, the average daily temperature was 24.2 ℃ and the average daily air humidity was 45.4% (**Figure 1**). Two treatments, conventional flood irrigation (CFI) and high-frequency drip irrigation (HDI), were set, and each treatment was repeated 10 times (basin). The tomato seedlings were transplanted into plastic POTS with a maximum diameter of 30 cm, a minimum diameter of 25 cm, and a height of 35 cm. Each pot was filled with 20 kg of soil (soil mass moisture content of 17.7%), and one seedling was transplanted. According to farmers' production habits, two treatments were applied: dry chicken manure with a nitrogen content of 2% as base fertilizer before pot loading, and the application rate was 3.90 g/kg soil. In addition, compound fertilizer (N, P_2O_5, K_2O mass ratio of 15:15:15) was also applied as base fertilizer in CFI treatment, and the application rate was 0.90 g/kg soil.

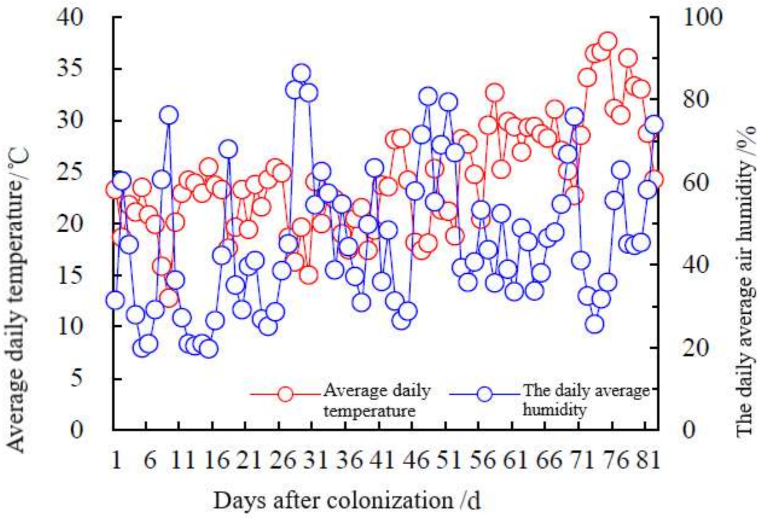

Figure 1. Changes of average daily air temperature and air humidity in the greenhouse during the experiment.

After colonization, 3.70 L/pot of colonization water was poured for both treatments, and plastic film was covered on the soil surface to prevent evaporation on the soil surface. After 17 days of colonization, irrigation and fertilization began. According to the different growth stages of tomatoes, the irrigation frequency of CFI treatment was 3–15 days, and the single irrigation amount was 3.00–4.00 L. Under membrane drip irrigation was used for HDI treatment; the frequency was 1-2 days; the single irrigation volume was 0.20–1.30 L; and no drip irrigation was used for overcast and rainy days. During the whole growth period, the total irrigation times of CFI treatment and HDI treatment were 13 times and 44 times, respectively, and the total irrigation amount was 42.75 L and 30.35 L, respectively. Topdressing was applied with each irrigation. After CFI treatment, no topdressing was applied in the first irrigation, and then 0.32 g/pot of pure nitrogen was applied each time. After HDI treatment, pure nitrogen was applied at 0.013–0.033 g/pot. The total nitrogen application in CFI and HDI treatments was 3.21 g/pot and 1.03 g/pot, respectively. For topdressing, a large amount of water-soluble fertilizer (N, P_2O_5, K_2O mass ratio is 21:21:21) was used. After each irrigation, water leakage was collected with a tray, and the volume of water leakage was measured with a measuring cylinder. When colonizing, the temperature and humidity recorder (model 8808, Hengxin Technology Co., LTD.) Is installed in the greenhouse, and the air temperature and humidity are recorded every 1 h. After 17 days of colonization, the plants were fixed with bamboo sticks to prevent lodging.

2.2. Sample collection and determination

At the time of basin loading, 200 g of soil was collected in a ziplock bag for the determination of the basic physical and chemical properties of organic soil. Soil organic carbon was determined by the potassium dichromate volumetric method and the external heating method. Soil alkali-hydrolytic nitrogen was determined by the alkali-hydrolytic diffusion method. The available soil phosphorus was extracted with 0.5 mol/L $NaHCO_3$ and determined by spectrophotometry. Soil-available potassium was extracted from 1.0 mol/L NH_4OAc and determined by flame photometry. Soil ph and *EC* values were extracted at a ratio of 5:1 water and soil and measured with a pH meter (IS126, Insmark, Shanghai) and electrical conductivity meter (DDSJ-308, Leizi, Shanghai). Soil mass water content was determined by the drying mass method[23].

The *SPAD* values of the latest fully expanded leaves of tomato plants were measured by a SPAD instrument (SPAD-502 Plus, Konica Minolta, Japan) from 09:30 to 10:00 on May 8, with three replicates per plant, and the average values were taken. From 09:30 to 11:30, a portable photosynthesis instrument (CIRAS-3, PP-Systems, America) was used to measure the stomatal conductance, transpiration rate, and instantaneous water use efficiency of the latest fully expanded leaves of tomato plants, with three replicates per plant, and the average values were taken.

The second panicle of tomato fruit was harvested by seedling pulling after ripening. The leaf area of each tomato plant was calculated by the punching weight method[24]. Then the tomato shoot was cut off, the stem, leaf, and fruit were separated, and they were put into a large envelope, respectively. After the fresh weight was weighed, the tomato was put into a 105 ℃ oven for 30 min and then dried at 75 ℃ to a constant weight to determine the dry weight of the shoot. Soil samples were taken from POTS with a soil drill with a diameter of 20 mm, and the mass water content of the soil at harvest was determined. After the oven-dried tomato leaves were crushed by a ball mill (MM200, Germany), the $\delta^{13}c$ values of the leaves were determined by a stable isotope ratio mass spectrometer (Thermo Delta V Advantage, Germany).

The calculation formula for relevant indicators in this paper is:

1) Transpiration (L) = soil water storage at colonization + irrigation – leakage – soil water storage at harvest – plant water content at harvest
2) Irrigation water utilization efficiency (G/L) = tomato shoot dry weight/irrigation volume
3) Water physiological use efficiency (G/L) = tomato shoot dry mass/transpiration

2.3. Data processing

Excel 2013 was used to process the data. SAS 8.0 was used for one-way analysis of variance, and Duncan's method was used for the significance test at 0.05 level. Sigmaplot 10.0 was used for plotting. Data in the table are presented as mean ± standard deviation.

3. Results and analysis

3.1. Effects of different irrigation methods on tomato biomass

The dry weight of tomato fruit under conventional flood irrigation and high-frequency drip irrigation was

22.0 g/plant and 21.0 g/plant, and the stem and leaf dry weight was 77.2 g/plant and 64.4 g/plant, respectively, with no significant difference between them (**Figure 2**).

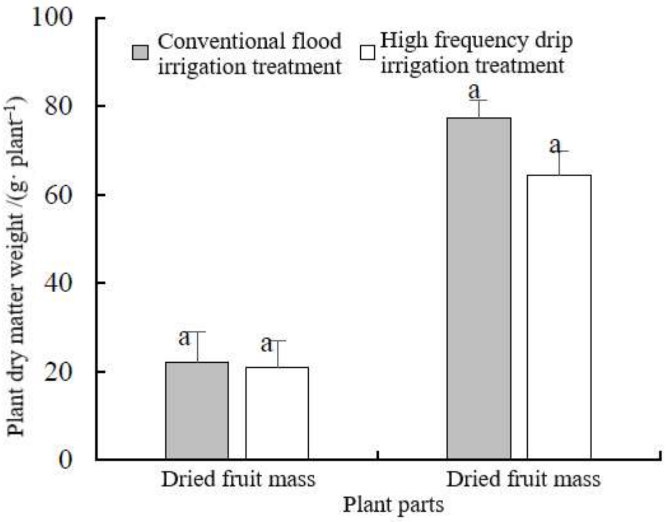

Figure 2. Tomato plant biomass under different irrigation treatments.

3.2. Effects of different irrigation methods on transpiration water consumption and water use efficiency of tomato

During the whole experimental period, the irrigation volume of conventional flood irrigation and high-frequency drip irrigation treatments was 42.75 L/pot and 30.35 L/pot, respectively (**Table 2**). Compared with the traditional flood irrigation treatment, the irrigation amount of the high-frequency drip irrigation treatment was reduced by 29.0%. The average water leakage in conventional flood irrigation treatment was 1.0 L/pot, while there was no water leakage in high-frequency drip irrigation treatment. Because the soil surface was always covered with plastic film during the experiment, the evaporation of the soil surface was temporarily negligible. According to the water balance, the transpiration of tomato plants under conventional flood irrigation and high-frequency drip irrigation were calculated to be 38.40 L/pot and 28.95 L/pot, respectively. The transpiration of tomato plants under high-frequency drip irrigation was 24.6% lower than that under traditional flood irrigation (**Table 2**). In addition, compared with the traditional flood irrigation treatment, the irrigation water use efficiency and water physiological use efficiency in the high-frequency drip irrigation treatment were significantly increased by 21.2% and 14.2%, respectively (**Figure 3**).

Table 2. Water balance of Tomato under different irrigation treatments.

Processing	Soil water storage/L during colonization	Irrigation quantity/L	Leakage/L	Soil water storage at harvest /L	Plant water content/L at harvest	Transpiration/L
The traditional flood irrigation	3.54	42.75	1.00 ± 0.20a	5.06 ± 0.17a	1.84 ± 0.09a	38.40 ± 0.16a
High-frequency drip irrigation	3.54	30.35	0b	3.36 ± 0.13b	1.58 ± 0.03b	28.95 ± 0.15b

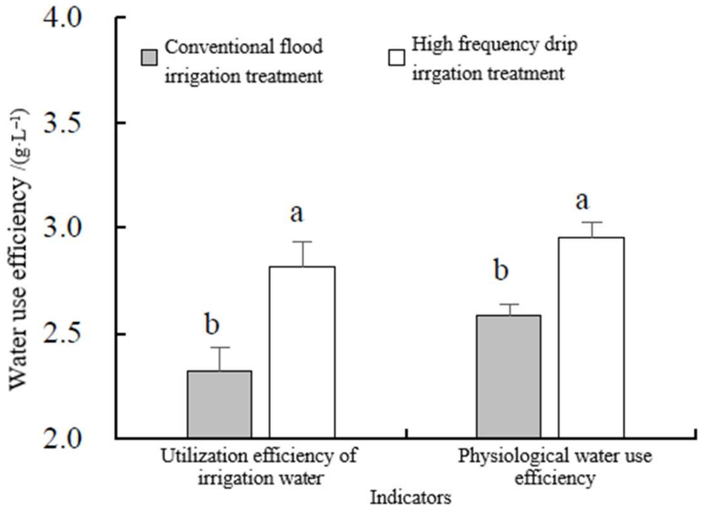

Figure 3. Irrigation water use efficiency and water physiological use efficiency under different irrigation treatments.

3.3. Effects of different irrigation methods on leaf area, stomatal conductance, transpiration rate and leaf δ13C of tomato

Compared with traditional flood irrigation, the leaf area, stomatal conductance, and transpiration rate of tomatoes were significantly decreased by 32.6%, 69.8%, and 54.3% under high-frequency drip irrigation, respectively. It significantly increased instantaneous water use efficiency and *SPAD* of tomato leaves by 21.6% and 14.5%, respectively (**Table 3**). In addition, the $\delta^{13}C$ values of tomato leaves under the two treatments were analyzed and it was found that the $\delta^{13}C$ values of tomato leaves under high-frequency drip irrigation were significantly higher than those under traditional flood irrigation (**Table 3**).

Table 3. Leaf area, stomatal conductance, transpiration rate and instantaneous water use efficiency under different irrigation treatments.

Processing	Leaf area/(cm^2·$plant^{-1}$)	Stomatal conductance/(μmol·m^{-2}·s^{-1})	Transpiration rate/(mmol·m^{-2}·s^{-1})	Instantaneous water use efficiency	*SPAD* values	Leaf blade $\delta^{13}C$
The traditional flood irrigation	11,974 ± 701a	126 ± 12.4a	4.6 ± 0.28a	3.7 ± 0.10b	50.9 ± 0.83b	–28.48 ± 0.24b
High-frequency drip irrigation	8066 ± 666b	38 ± 4.6b	2.1 ± 0.21b	4.5 ± 0.22a	58.3 ± 0.64a	–27.71 ± 0.12a

4. Discussion

This study shows that, compared with traditional flood irrigation, high-frequency drip irrigation significantly reduces irrigation amount and improves irrigation water utilization efficiency, which is consistent with the results of previous studies[11,25]. In addition, this study also showed that high-frequency drip irrigation significantly reduced tomato transpiration consumption and improved water physiological use efficiency (**Table 2** and **Figure 3**), which is similar to previous studies[26], namely, reducing soil water content can significantly reduce water consumption of winter wheat and improve transpiration efficiency. The difference is that Changhai et al.[26] showed that the biomass of winter wheat in the treatment of reducing soil water content was significantly reduced, while in this study, there was no significant difference in the fruit and stem and leaf dry weight of tomato in the treatment of high-frequency drip irrigation and traditional flood irrigation ($p > 0.05$, **Figure 2**). The author thinks that water control irrigation should be carried out under the premise of guaranteeing crop yield.

Plant leaf photosynthesis and transpiration of stomatal conductance of the sensitivity of different, the relationship between them is nonlinear, with the increase of photosynthetic active radiation and leaf stomatal conductance increased, when the photosynthetic active radiation after reaching the light saturation point and stomatal conductance after reaching a certain value, photosynthetic rate remains unchanged, and transpiration rate is still a linear increase, At this time, the phenomenon of "luxury transpiration" will appear[27–28]. Luxury transpiration leads to invisible and ineffective water loss, which reduces water use efficiency and exacerbates water pressure in water-scarce areas in northern China. Luxury transpiration of winter wheat in the North China Plain accounted for 6.8%–9.4% of the total transpiration[12]. Therefore, reducing luxury transpiration can achieve physiological water savings for crops, which is crucial for the efficient utilization of agricultural water resources[17].

Plant transpiration is closely related to leaf area and stomatal conductance. Therefore, by regulating leaf area and stomatal conductance, the balance between photosynthesis and transpiration can be achieved, so as to reduce ineffective transpiration and improve water physiological use efficiency. Plant transpiration was significantly positively correlated with leaf area index [29], which was consistent with this study (**Tables 2** and **3**). In addition, leaf stomatal conductance is closely related to plant water status. Adequate water supply will lead to an increase in the stomatal conductance of leaves, accelerate water transport, and thus increase transpiration [26]. This was consistent with the results of this study, namely, stomatal conductance, transpiration rate, and transpiration water consumption of tomato leaves under conventional flood irrigation were 3.3, 2.2, and 1.3 times higher than those under high-frequency drip irrigation, respectively (**Table 2** and **Table 3**).

In ecological studies, the leaf $\delta^{13}c$ value is often used to indicate the long-term WUE of plants. This method is superior to conventional photosynthometer measurement because the results of photosynthometer measurement can only represent the WUE of plants at the time of measurement, while the leaf $\delta^{13}c$ value can indicate the WUE of plants during the whole growth period[30]. When there is a water deficit in plants, leaf stomatal conductance is reduced, thereby reducing transpiration water consumption, and stomatal conductance decreases the number of atmospheric CO_2 in plants. Plant photosynthetic assimilation of CO_2 is relatively more likely from plant respiration, so the carbon isotope effect will occur and lead to a rise in the $\delta^{13}C$ value[31]. This study showed that the $\delta^{13}C$ value and water physiological use efficiency of tomato leaves under high-frequency drip irrigation were significantly higher than those under traditional flood irrigation (**Table 3**), indicating that during the whole growth period, compared with traditional flood irrigation, tomato plants under high-frequency drip irrigation were in a certain state of water deficit and had higher water use efficiency. Osorio et al.[32] showed that leaf $\delta^{13}c$ value was positively correlated with transpiration efficiency, which was consistent with this study. In this study, the water balance method was used to calculate the total water consumption of tomatoes during the whole growth period. However, the quantity of luxury transpiration and the occurrence of luxury transpiration of tomatoes in facilities need further study.

5. Conclusion

High-frequency drip irrigation can not only significantly improve the utilization efficiency of irrigation water but also regulate tomato plants in a moderate water deficit state. By reducing leaf area, stomatal conductance, and transpiration rate, transpiration water consumption can be significantly reduced, and physiological water use efficiency can be improved, so as to achieve physiological water savings. Therefore, the drip irrigation method of "a small number of times" is one of the important measures to realize efficient utilization of water resources, which is worth promoting in the production of tomatoes in the north facilities.

Conflict of interest

The authors declare no conflict of interest.

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