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Full Length Article

Effect of Stable Negative Pressure Irrigation on the Growth and Development of Eggplant (*Solanum melongena*)

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Abstract

This study was conducted with an objective to determine the optimal negative pressure irrigation suitable for growth and development of eggplant. The total water consumption, yield, growth and development, physiological activity, and quality of eggplant were tested using a pot experiment in a greenhouse with four treatments, namely -3, -8, -15 kPa and normal irrigation (C). The negative pressure was maintained using a stable negative pressure irrigation device. The total water consumption of eggplant was decreased by 20.51–70.00%, the total water consumption intensity was decreased by 22.18–70.27%, and the water use efficiency was increased by up to 7.45–41.48% under negative pressure irrigation compared with control (C). When the irrigation pressure was controlled at -3 kPa, the nitrate reductase activity, root activity, and chlorophyll content were increased by 6.14–15.5%, 11.11–33.33% and 20.04–51.58%, respectively. The yield of eggplant was also increased by 12.43% compared with control. The soluble sugars, soluble protein, and vitamin C contents of eggplant fruits at different maturation stages were increased by 14.47–47.22%, 16.33–58.78%, and 19.64–43.42% at -3 kPa, respectively, compared with the control. Taken together, it was observed that stable negative pressure irrigation in the range of -3 to -15 kPa obviously reduced water consumption of eggplant, and had a water saving effect. Negative pressure irrigation (-3 kPa) improved the water use efficiency, physiological activity, growth and development, and yield and quality of eggplant.

Keywords: Negative pressure irrigation; Water conservation; Water use efficiency; Yield improvement, Growth and development

Introduction

Eggplant (*Solanum melongena* L.) is one of the main vegetables consumed in China (Lian *et al.* 2017). The eggplant has tap root system and has low tolerance for drought. It is highly sensitive to water supply; soil water deficit, excessive water content, and variation in soil moisture content substantially affect the growth and development and yield and quality of eggplant (Tong *et al.* 2013). Thus, a method to reduce water loss and improve water use efficiency for eggplant is required for quality production. At present, several water-saving irrigation methods using sophisticated equipment are widely employed in agriculture such as sprinkler irrigation, drip irrigation, and infiltration irrigation (Hu and Yu 2002; Li *et al.* 2004; Wu 2004). Although the aforementioned methods can effectively improve water use efficiency, however, these are prone to surface runoff resulting in wastage of water resources, loss of nutrients, and soil compaction (Clinton *et al.* 2001). The traditional flood irrigation method causes loss of water resources, enhances evaporation and reduces soil temperature. Excessive evaporation causes increased air humidity in greenhouses that reduces rate of transpiration of the leaves, resulting in reduced root water uptake and increases probability of groundwater pollution caused by diseases, pests, and percolation of nutrients (Wu *et al.* 2002). A new type of automatic recharge water-saving irrigation technology was used in this experiment in order to reduce wastage of water and improve water use efficiency (Wang *et al.* 2015). The stable negative pressure irrigation technology utilizes soil suction and the ability of plant to absorb water actively to supplement soil moisture, and regulates the soil moisture content in the root zone during the entire growth period of the crop. This method promotes crop growth, improves crop yield and helps control the disadvantages of traditionally followed irrigation methods (Liu *et al.* 2000a, 2000b). In 1908, Livingston first proposed the concept of water absorption using matrix potential (Livingston 1908). Different scientists have explored this concept theoretically, and verified the feasibility of negative pressure irrigation with an automatic water supplying device (Richards and Loomis 1942; Kato 1982; Lei *et al.*

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2005). Zou *et al.* (2007) found that the negative pressure irrigation system can automatically supply water timely and appropriately without being affected by external factors and reduces water loss from the soil caused by percolation and evaporation. According to another report, if negative pressure irrigation is employed on a large scale it has a water saving effect and requires less energy (Liu 2001). According to a report, Li *et al.* (2017) planted pepper using negative pressure water supply device, and the results showed that negative pressure irrigation at -5 kPa was beneficial for the growth and development of pepper, promoted nutrient absorption and improved the quality of pepper. Negative pressure irrigation technology has been applied in several other crops. It can promote crop growth, improves water use efficiency, increases yield, and improves fruit quality (Li *et al.* 2008a; Li *et al.* 2010; Xiao *et al.* 2015). During recent past, the application of negative pressure irrigation on eggplant has been reported but those studies were only focused on the effect of specific negative pressure irrigation on the growth and physiological characteristics of eggplant (Li *et al.* 2016). However, the effects of different water supply pressures on the growth and development of eggplant, water use efficiency, physiological characteristics, and quality have not been reported. Therefore, in this study, stable negative pressure irrigation device was used to control the soil water potential in the range of -3 to -15 kPa for eggplant, to determine the effect of different negative pressures on water consumption, dry matter accumulation, physiological parameters, and quality of eggplant. The main objective of this study was to find out the suitable negative pressure for irrigation of eggplant.

Materials and Methods

Experiment material

The experiment was carried out from May to October, 2017 in a rainproof plastic greenhouse with a steel frame structure in the experimental base of Heilongjiang Bayi Agricultural University, Daqing, Heilongjiang, China. The seedlings of eggplant cultivar 'Black and Bright' were obtained from the breeding base of Heilongjiang Bayi Agricultural University, China for this study. 'Black and Bright' is a popular cultivar of eggplant that is cultivated on a commercial scale in Heilongjiang province of China. The upper 0–20 cm soil was used for pot filling and those pots were used in this study. The soil used for this experiment was analyzed. Soil had a pH of 8.4, organic matter 27.88 $g \cdot kg^{-1}$, available phosphorus 30.7 $mg \cdot kg^{-1}$, available potassium 168.5 $mg \cdot kg^{-1}$, and alkali-hydrolyzed nitrogen 93.3 $mg \cdot kg^{-1}$. Each pot was filled with 33 kg of 1 cm sieved soil.

Stable negative pressure irrigation control device

The negative pressure irrigation device used in the experiment was developed by Institute of Agricultural Resources and Regional Planning of Chinese Academy of Agricultural Sciences (Long *et al.* 2014). It consists of three parts: the water outlet, water storage barrel and negative pressure stabilizer. Each part is connected by an organic transparent plastic hose. Among them, the water outlet is a "water permeable and air impermeable" clay pipe (inner diameter 11 mm, outer diameter 18 mm, length 250 mm), the water tank is 75 cm high, and the side wall is equipped with 50 cm of high graduated tube; which is used to observe the change of water level in the tank. The negative pressure stabilizer is mainly composed of three parts: the negative pressure tank, digital display switch and solenoid valve. The digital display switch sets the required negative pressure value. The needed water for plant growth reduces the soil water potential compared with pressure set by the negative pressure stabilizer; the water within the water storage barrel permeates into the soil slowly under suction pressure of the soil. When the water within the water storage barrel enters the clay pipe through the plastic hose, the water level in the barrel is dropped, the pressure within the barrel decreased until the internal pressure of the negative pressure tank reached the set value of the digital display switch and continued to decrease, and the solenoid valve is opened, causing a certain amount of outside air to enter the negative pressure tank (Li *et al*. 2017). When the internal pressure of the negative pressure tank reaches the set value of the digital display switch, the solenoid valve closes, to maintain a stable negative water supply pressure. The size of the pot was 30 cm × 30 cm × 45 cm, there were no holes in the bottom and the floor of pot was flat. The clay pipe was inclined by 5 degrees and buried in the soil; it was positioned 10 cm from the front and back of the inner wall of the pot, 14.1 cm from the left and the right inner wall, and 10 cm below the surface of the soil in the pot. The pattern of the stable negative pressure irrigation device is illustrated in Fig. 1. According to the principle of negative pressure infiltration; negative pressure irrigation technology uses the difference between soil water potential (soil suction) and water supply pressure of irrigation system as the driving force for irrigation water to enter in the soil. This fulfills an irrigation method that replenishes soil water in the crop root zone, which is essentially a process in which irrigation water gradually wets the soil in a certain area by means of capillary action through an irrigator buried underground.

Experimental treatment

Four irrigation treatments were set up for the pot experiment: C (normal irrigation, control), -3 (T1), -8 (T2) and -15 kPa (T3). Basal dose of fertilizer was applied before transplanting and the amount of fertilizer for application was calculated according to the local recommendation (N = 150 $mg \cdot kg^{-1}$ soil; P_2O_5 = 100 $mg \cdot kg^{-1}$ soil; K_2O = 150 $mg \cdot kg^{-1}$ soil). The fertilizer and sieved soil were mixed in each pot. A completely randomized experimental design was used for this study. Three pots containing four plants in each pot were used for every treatment, and each treatment was replicated three times. Pots were placed at 20 cm row spacing. Each set had an automatic water supply device that controls a pot with a total of nine sets. The water level of each automatic water supply device was recorded at 17:00 P.M. every day. The potted plants used as control (C) were irrigated manually when 5 cm of the topsoil of pot become dry, and every time 550 mL water was used for irrigation of a single pot.

Sample collection

The samples were harvested four times: at early flowering stage (June 21, 2017), early fruit-bearing stage (July 12, 2017), full fruit-bearing period (August 01, 2017) and late growth stage (September 01, 2017). Samples were harvested at 6:30 A.M, however, sample for determining enzyme activities were harvested at 9:30 A.M. One representative plant was harvested from each pot for each treatment. The samples of eggplant fruit were taken four times: the first set of fruit (July 12, 2017), the second set of fruit (July 26, 2017), the third set of fruit (July 31, 2017), and the fourth set of fruit (August 31, 2017).

Water consumption determination

Water consumption was analyzed based on the following formulas:

(1) Negative pressure irrigation: Water consumption (kg strain^{-1}) = Δh (cm) × area (cm^2) / total number of pots.

Where, Δh is the height difference between each record; area is the internal floor area of storage barrel for the negative pressure irrigation and total number is the number of eggplant pots.

(2) C: Water consumption (kg strain^{-1}) = Irrigation volume (L) used in a unit of time / total number of pots of eggplant.

Where, irrigation volume (L) used in a unit of time was 550 mL for each pot and it was applied when upper 5 cm topsoil of pot become dry.

Water use efficiency

Water use efficiency was calculated using the following formula: Water use efficiency (g L^{-1}) = Yield (g strain^{-1}) / Water consumption (L strain^{-1}).

Water consumption percentage

Water consumption percentage was calculated using the following formula: Water consumption percentage = Water consumption at a certain growth stage (mm) / total water consumption at the growth stages (mm) × 100.

Nitrate reductase determination

Nitrate reductase activity was determined using the aminobenzene sulfonic acid colorimetric method (Zhou and Zhen 1985).

Determination of rhizosphere activity

Rhizosphere activity was determined using the α-naphthylamine oxidation method (Chang *et al.* 2008).

Determination of chlorophyll

Chlorophyll *a* and Chlorophyll *b* contents were determined using the alcohol extraction method (Bai 1990).

Determination of vitamin C (VC) content

The VC content was determined using 2, 6-diohloroindophenol potentiometer titration (Zhao *et al.* 2006).

Determination of soluble sugars

The soluble sugar contents were determined using anthrone colorimetric technique (Zou 2000).

Determination of soluble protein content

The soluble protein contents were determined using Coomassie Brilliant Blue G250 staining (Li *et al.* 2002).

Determination of above ground dry weight

The above ground dry biomass was measured by taking the above ground plant parts such as leaves, stems, leaf stalks, and fruit of the eggplant at different stages. Initially the samples were placed at 105°C for 30 min, and then dried at 75℃ until the mass was constant, finally, the dry mass of each part was weighed (Xu *et al.* 2014)

Data analysis

Microsoft Excel 2010 was used for data coding. S.P.S.S. 19.0 (IBM 2010) was used for statistical analysis, and multiple comparisons were done using least significant difference (LSD) test at $P \leq 0.05$.

Results

Effect of stable negative pressure irrigation on water consumption, yield, and water use efficiency of eggplant

It was observed that under normal irrigation (C) and negative pressure irrigation treatments, the water consumption per plant and water consumption intensity increased gradually with plant development during the growth period (Table 1). Water consumption per plant and water consumption intensity was observed in the following order: the early flowering stage < the early fruit-bearing stage < the full fruit-bearing period < the late growth stage. The total water consumption percentage was highest at the

Table 1: Effect of stable negative pressure irrigation on water consumption of eggplant. C, normal irrigation; -3, -8 and -15 kPa

Growth period	Treatments	Water consumption (L plant^{-1})	Water consumption intensity (L d^{-1})	Total water consumption percentage (%)
Early flowering stage	Control	3.71 a	0.25	4.95
	-3 kPa	3.26 b	0.22	5.48
	-8 kPa	2.51 c	0.17	4.97
	-15 kPa	1.81 d	0.12	8.06
Early fruit bearing stage	Control	15.40 a	0.67	20.55
	-3 kPa	7.97 b	0.35	13.39
	-8 kPa	7.25 b	0.32	14.48
	-15 kPa	3.98 c	0.17	17.64
Full fruit bearing period	Control	19.68 a	1.09	26.26
	-3 kPa	15.81 b	0.88	26.54
	-8 kPa	12.32 c	0.68	24.43
	-15 kPa	5.06 d	0.28	22.53
Late growth stage	Control	36.15 a	0.95	48.24
	-3 kPa	32.52 b	0.86	54.59
	-8 kPa	28.34 c	0.75	56.21
	-15 kPa	11.63 d	0.31	51.77

Different letter along the mean values represent significant differences among the means using least significant test at $P \leq 0.05$

Table 2: Effect of stable negative pressure irrigation on yield and water use efficiency of eggplant. C, normal irrigation; -3, -8 and -15 kPa

Indexes	Treatments			
	Control	-3 kPa	-8 kPa	-15 kPa
Total water consumption(L)	74.94 a	59.57 b	50.42 c	22.48 d
Yield (g strain^{-1})	1316.20 b	1479.86 a	1084.32 c	422.03 d
Water use efficiency (g L^{-1})	17.56 c	24.85 a	21.51 b	18.87 c

Different letter along the mean values represent significant differences among the means using least significant test at $P \leq 0.05$

Table 3: Effect of stable negative pressure irrigation on growth and development of eggplant. C, normal irrigation; -3, -8 and -15 kPa

Growth period	Treatments	Plant height (per plant cm^{-1})	Stem diameter (per plant mm^{-1})	Dry weight (per plant g^{-1})
Early flowering stage	Control	44.50 b	6.81 b	7.18 c
	-3 kPa	55.90 a	8.51 a	11.53 a
	-8 kPa	45.07 b	7.24 ab	8.74 b
	-15 kPa	32.60 c	6.02 b	4.93 d
Early fruit bearing stage	Control	60.80 b	8.00 b	20.09 a
	-3 kPa	72.83 a	9.28 a	20.31 a
	-8 kPa	62.23 b	7.79 b	16.29 b
	-15 kPa	46.43 c	6.42 c	6.00 c
Full fruit bearing period	Control	79.03 b	11.75 a	33.75 a
	-3 kPa	91.03 a	12.26 a	34.66 a
	-8 kPa	71.90 c	10.20 b	29.81 b
	-15 kPa	57.63 d	7.17 c	13.92 c
Late growth stage	Control	104.97 b	12.10 b	54.11 b
	-3 kPa	126.17 a	14.98 a	60.99 a
	-8 kPa	94.10 c	11.72 b	47.48 c
	-15 kPa	74.83 d	9.02 c	34.96 d

Different letter along the mean values represent significant differences among the means using least significant test at $P \leq 0.05$

late growth stage, where it reached to 48.24 to 51.77%. The results of this study showed that eggplant requires more water in the middle and late growth stages.

With stable negative pressure irrigation, water consumption and water consumption intensity per plant were lower compared with control (C). Irrigation pressure was controlled between -3 and -15 kPa; it was observed that the water consumption and water consumption intensity for each treatment was decreased by reducing the irrigation pressure. The total water consumption per plant for -3, -8 and -15 kPa treatments with stable negative pressure irrigation were 20.51, 32.72 and 70.00% lower compared with control. And water consumption in each growth period was apparently different from control (Table 2). The total water consumption intensities per plant in the -3 kPa, -8 and -15 kPa treatments were 22.18, 35.24 and 70.27% lower compared with control, and the difference between the control and negative pressure irrigation was significant. Considering the results of this study, we concluded that water consumption of eggplant can be adjusted by controlling the pressure of irrigation. By lowering the pressure, less water is consumed by the eggplant that reduces water consumption intensity.

The results showed that negative pressure irrigation was positively correlated with eggplant fruit yield and water use efficiency (Table 2). The yield of eggplant for different irrigation treatment varies as: -3 kPa > CK > -8 kPa > -15 kPa. The yield of eggplant for -3 kPa treatment was significantly higher (12.43%) compared with control, and the yield of eggplant for -8 and -15 kPa was 17.62 and 67.94% lower, respectively compared with control. This indicated that controlling the irrigation pressure could increase fruit yield; and when the irrigation pressure is too low that reduces fruit yield.

The water use efficiency of -3, -8 and -15 kPa treatments with stable negative pressure irrigation was 41.48, 22.45 and 7.45% higher compared with control. The differences between -3 and -8 kPa, and control were significant while the difference between the -15 kPa and control was non-significant. The results show that water use efficiency of eggplant can be improved by controlling the pressure the irrigation pressure between -3 to -8 kPa.

Effect of stable negative pressure irrigation on the growth and development of eggplant

The results of the agronomic traits and dry matter accumulation of eggplants at different growth stages (Table 3) showed that plant height at -3 kPa (T1) was apparently higher compared with control plants during the whole growth period. The plant height of plant at -3 kPa was increased by 25.62, 19.79, 15.18 and 20.20% at early flowering stage, early fruit-bearing stage, full fruit-bearing period, and late growth stage, respectively, compared with control. There was no significant difference between the height of eggplants grown under control conditions compared with -8 kPa during the early growth period (from early flowering stage to early fruit-bearing stage), however, the height of -8 kPa plants was lower compared with control from full fruit-bearing period to the late growth stage. The height of eggplant at -15 kPa was significantly lower

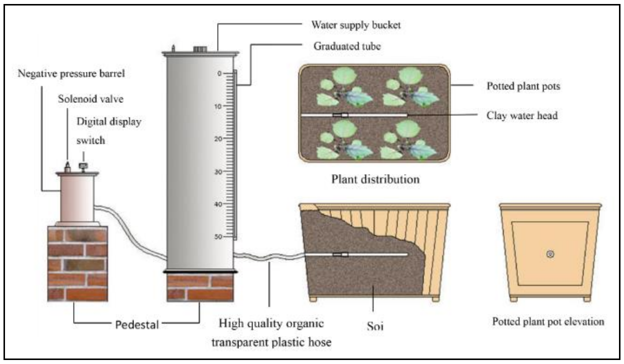

Fig. 1: Sketch of stable negative pressure irrigation control device used in this study

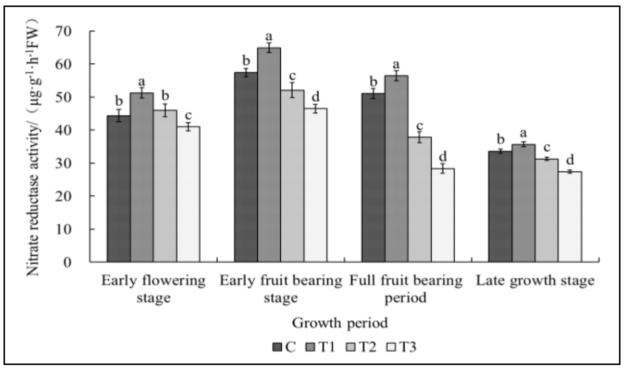

Fig. 2: Effect of stable negative pressure irrigation on nitrate reductase activity of eggplant. FW, fresh weight; C, normal irrigation; -3, -8 and -15 kPa. Error bars indicate SE. Different letter above the bars represent significant differences among the means using least significant test at $P \leq 0.05$

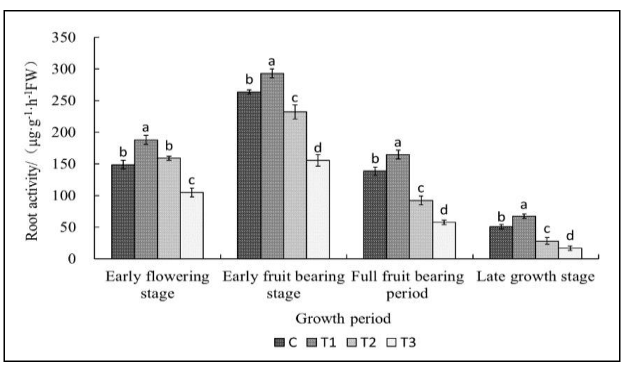

Fig. 3: Effect of stable negative pressure irrigation on the root activity of eggplant. FW, fresh weight; C, normal irrigation; -3, -8 and -15 kPa. Error bars indicate SE. Different letter above the bars represent significant differences among the means using least significant test at $P \leq 0.05$

compared with control plants from the early fruit-bearing stage to the late growth stage.

By analyzing the results, it was observed that stem diameter was improved by up to 24.98% for the -3 kPa plant compared with control (C) at early flowering stage, and there was no difference for other treatments compared with control. From the early flowering stage to the late growth stage, the stem diameter was increased for -3 kPa plants by 22.31% compared with control. The stem diameter increment difference between -8 and -15 kPa treatment was significantly lower compared with control.

The morphological indicators of the eggplant showed that plant height and stem diameter was significantly improved (Table 3) compared with control during the entire growth period of eggplant when the irrigation pressure was maintained at -3 kPa. This indicates that negative pressure irrigation is beneficial for the growth and development of eggplant.

From transplanting to the early flowering stage, the dry matter accumulation of eggplant varied in this order: -3 kPa > -8 kPa > CK > -15 kPa (Table 3). From the early flowering stage to the full fruit-bearing period, the dry matter accumulations for control plants was significantly higher compared with -8 and -15 kPa plants. There was no significant difference between the control and -3 kPa plants. At the late growth stage of eggplant, the dry matter accumulation for the plants grown under negative pressure irrigation was significantly increased compared with control. The plants grown at -3 kPa had 12.71% higher dry matter accumulation compared with control, suggesting that the negative pressure irrigation is beneficial for dry matter accumulation of eggplant.

The number of eggplant fruits at different maturation stages increased gradually with plant development (Table 4). There was no significant difference for the number of eggplant fruits per plant between other treatments compared with control, except -15 kPa. Under negative pressure irrigation (-3 and -15 kPa), the weight of eggplant fruits at different maturation stages increased with the growth stages. The single eggplant fruit weight at different maturation stages (the first, second and third set of fruit) for -3 kPa treatment was 9.88, 27.56 and 30.83% higher compared with control, respectively. The results showed that negative pressure irrigation at -3 kPa was beneficial for eggplant fruit development.

Effect of stable negative pressure irrigation on the nitrate reductase activity, root activity, and chlorophyll content of eggplant

The results showed that the nitrate reductase activity of eggplant leaves was increased with the development and it decreased after the full fruit-bearing period (Fig. 2). The highest nitrate reductase activity of eggplant leaves for all treatments was observed at the early fruit-bearing stage (-3 kPa > CK > -8 kPa > -15 kPa). Nitrate reductase activity for -3 kPa was 15.50, 13.06, 10.53 and 6.14%, higher at early flowering stage, early fruit-bearing stage, full fruit-bearing period and late growth stage, respectively, compared with control. The nitrate reductase activity of -8 kPa plants at the early flowering stage had no significant difference compared

Table 4: Effect of stable negative pressure irrigation on eggplant fruits. C, normal irrigation; -3, -8 and -15 kPa

Fruiting section	Indexes	Treatments			
		Control	-3 kPa	-8 kPa	-15 kPa
First set of fruit	Number (per plant)	1	1	1	1
	Fresh weight (g)	122.43 b	134.53 a	104.51 c	63.50 d
Second set of fruit	Number (per plant)	2	2	2	2
	Fresh weight (g)	133.28 b	170.02 a	123.79 c	79.49 d
Third set of fruit	Number (per plant)	3	3	3	2
	Fresh weight (g)	87.43 c	114.38 a	75.66 d	99.78 b
Fourth set of fruit	Number (per plant)	4	4	3	0
	Fresh weight (g)	166.23 a	165.54 a	126.31 b	0

Different letter along the mean values represent significant differences among the means using least significant test at $P \leq 0.05$

Table 5: Effect of stable negative pressure irrigation on chlorophyll content of eggplant. C, normal irrigation; -3, -8 and -15 kPa

Date	Treatments	Chlorophyll a (mg g^{-1})	Chlorophyll b (mg g^{-1})	Chlorophyll (a + b) (mg g^{-1})	Chlorophyll a/b
Early flowering stage	Control	1.37 c	0.57 b	1.94 ± 0.13 c	2.41
	-3 kPa	2.25 a	0.78 a	2.95 ± 0.39 a	2.76
	-8 kPa	1.89 b	0.61 b	2.5 ± 0.08 ab	3.08
	-15 kPa	1.74 b	0.62 b	2.35 ± 0.12 bc	2.84
Early fruit bearing stage	Control	1.36 b	0.51 b	1.87 ± 0.11 b	2.68
	-3 kPa	1.66 a	0.63 a	2.29 ± 0.20 a	2.62
	-8 kPa	1.11 bc	0.46 b	1.57 ± 0.19 bc	2.39
	-15 kPa	0.93 c	0.44 b	1.37 ± 0.16 c	2.14
Full fruit bearing period	Control	1.36 b	0.54 ab	1.90 ± 0.17 b	2.54
	-3 kPa	1.67 a	0.60 a	2.28 ± 0.25 a	2.78
	-8 kPa	1.26 b	0.49 b	1.76 ± 0.11 b	2.58
	-15 kPa	0.95 c	0.37 c	1.31 ± 0.19 c	2.58
Late growth stage	Control	1.27 b	0.43 b	1.71 ± 0.20 b	2.93
	-3 kPa	1.64 a	0.54 a	2.18 ± 0.19 a	3.05
	-8 kPa	0.97 c	0.32 c	1.29 ± 0.07 c	3.04
	-15 kPa	0.76 d	0.21 d	0.97 ± 0.04 d	3.58

Different letter above the bars represent significant differences among the means using least significant test at $P \leq 0.05$

with control; however, it was significantly lower compared with control at other growth stages. The nitrate reductase activity of the -15 kPa plants was significantly lower compared with control at all stages of plant growth and development.

Considering whole growth period of eggplant, the changing trends for root activity was observed for different growth stages (Fig. 3). The highest root activity was observed at early fruit-bearing stage, and then root activity was decreased. For all growth stages of eggplant, the root activities of the -8 and -15 kPa plants decreased to different degrees with decreasing irrigation pressure compared with control. The root activity for -3 kPa plants was significantly higher for all growth stages of the eggplant compared with control (11.11–33.33%). From the results it was concluded that appropriate negative irrigation pressure is conducive for the improvement of nitrate reductase activity and root activity that helps improve eggplant plant growth and development. The nitrate reductase activity and root activity were higher when the irrigation pressure is maintained at -3 kPa.

It was observed that negative pressure irrigation affected the chlorophyll content of eggplant. The chlorophyll (*a*, *b*, and *a* + *b*) contents at different growth stages of eggplant grown under stable negative pressure irrigation and control conditions were highest at the early flowering stage (Table 5). The changes in chlorophyll (*a*, *b*, and *a* + *b*) contents under all treatments were relatively stable from the early fruit-bearing stage to the full fruit-bearing period. The chlorophyll (*a*, *b*, and *a* + *b*) content of eggplant increased gradually when the irrigation pressure increased over the whole growth period. The chlorophyll contents of -3 kPa plants were 51.58, 22.84, 20.04 and 27.66% higher compared with control at early flowering stage, early fruit-bearing stage, full fruit-bearing period, and late growth stage, respectively, compared with control. The results showed that appropriate irrigation pressure (-3 kPa) was conducive to increase the chlorophyll content, however, too low irrigation pressure resulted in water deficiency, inhibiting the biosynthesis of chlorophyll in eggplant leaves.

Effect of stable negative pressure irrigation on the quality of eggplant

Soluble sugar, soluble protein, and vitamin C contents are important nutrients and considered as quality indicators for the vegetables (Tavarini *et al.* 2008). Soluble sugar and protein contents of eggplant were different at different maturation stages (the first, second, third, and fourth sets of fruit). Soluble sugar and protein contents of eggplant were highest in the second set of fruit, and vitamin C content was highest in the third set of fruit (Fig. 4). The soluble sugar content of eggplant for -3 kPa was increased by 47.22, 19.22, 19.43 and 14.47% at the first, second, third, and fourth sets of fruit compared with control, respectively. The soluble sugar content in the first set of -8 kPa fruits was 25.63% higher compared with control, however, the soluble sugar content of eggplant fruit at other fruiting stages (second, third, and fourth sets of fruit) were lower compared with control.

The soluble protein content of eggplant fruit grown under two irrigation systems was analyzed. The soluble protein content of eggplant fruit at different maturation stages for -3 kPa increased by up to 16.33–58.78% compared with control. The first set of eggplant fruits of -8 kPa has 31.20% increased soluble protein content compared with control, however for other sets of fruits (second, third, and fourth set of fruit) the soluble protein content were gradually decreased compared with control. There was an obvious decrease in the soluble protein content of eggplant fruit at different maturation stages, and soluble protein content of -15 kPa plants were reduced from 26.25 to 34.43% compared with control.

It was observed that vitamin C content in eggplant fruit decreased significantly when the irrigation pressure was decreased. The vitamin C contents of eggplant grown at -3 kPa were 43.42, 25, 19.64 and 41.79% higher at first, second, third and fourth set of fruit compared with control, respectively. Except the fruits of first set of fruit of -8 kPa, vitamin C content in other treatments showed no significant

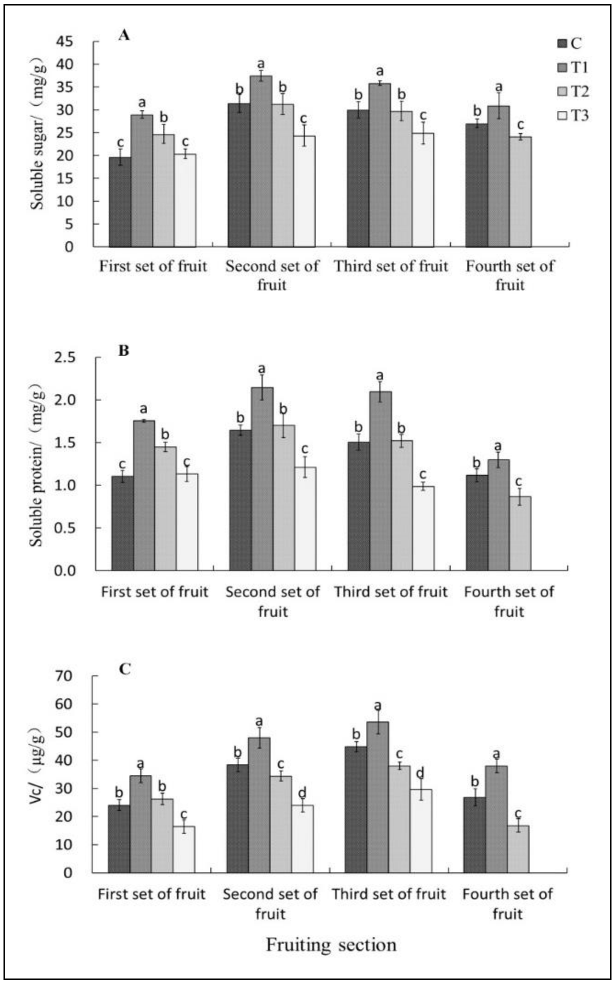

Fig. 4: Effect of stable negative pressure irrigation on the fruit quality of eggplant. **A**: Effect of stable negative pressure irrigation on the soluble sugar of eggplant, **B**: Effect of stable negative pressure irrigation on the soluble protein of eggplant, and **C**: Effect of stable negative pressure irrigation on the VC of eggplant. VC: Vitamin C; C, normal irrigation; -3, -8 and -15 kPa. Error bars indicate SE. Different letter above the bars represent significant differences among the means using least significant test at $P \leq 0.05$

difference compared with control. The vitamin C content in other fruiting stages (second, third, and fourth set of fruit) grown under -8 kPa were significantly lower (0.42–37.31%) compared with control. It can be observed that the quality of eggplant fruit can be improved when the irrigation pressure is maintained at -3 kPa, however further reduction of irrigation pressure lead towards the decline of eggplant fruit quality.

Discussion

The negative pressure irrigation device is a closed water supply system that uses the water potential difference between the system and the soil to achieve automatic crop water acquisition (Geng *et al.* 2006). Considering the energy analysis, it is proposed that the unit water potential inside the irrigator is φin and the unit soil water potential outside the irrigator is φout, when φin - φout is positive, the irrigation water will flow into the soil from the irrigator; the condition for the irrigator to stop the outflow is when φin - φout is zero (Cai *et al.* 2017). The results of this study showed that the eggplants continuously absorbed water, and at this time φin > φout, the irrigation water was automatically added to the root soil of the eggplant during its growth. The water supply mode of the irrigation device was constant; therefore, the soil water content could be maintained within a relatively stable range. The water consumption during the growth period of the eggplant could be effectively reduced, which is consistent with the findings of previous reports (Li *et al.* 2008b; Liang *et al.* 2011). The results showed that the water consumption of eggplant grown under control conditions and negative pressure irrigation was increased with the development of the eggplant, which was different from the results of Du *et al.* (2018). This may be due to the differences in greenhouse environment, and the longer growth period from the full fruit-bearing period to the late growth period of eggplant. Higher indoor temperature during the daytime increases the consumption of unproductive water such as water used for evapotranspiration, which leads to an increase in water consumption at the late growth stage of the eggplant. The results also showed that the water consumption of eggplant with negative pressure irrigation was apparently decreased by decreasing irrigation pressure during the whole growth period. The water consumption of eggplant was significantly decreased compared with control. This may be because of increase in the photosynthetic rate during the negative pressure irrigation treatment, which significantly decreases the leaf water potential and stomatal conductance, thus affects plant transpiration (Liu *et al.* 2010).

Water use efficiency (WUE) is one of the most important indicators of crop water use (Li *et al.* 2008b). With the help of the difference between the soil water potential (soil suction) and the pressure of the irrigation system, the negative pressure irrigation treatment was used as the driving force for the irrigation water to enter the rhizosphere of the soil (Jiang *et al.* 2006). The realization that the purpose of demand-based water supply provided an appropriate water environment for the growth of eggplant also laid a foundation for the efficient use of water. The results showed that negative pressure irrigation could significantly improve the WUE of eggplant compared with control. The water use efficiency was increased by enhancing the negative pressure used for irrigation; the water use efficiency was highest at -3 kPa and lowest at -15 kPa for eggplant. The highest yield per plant was obtained from the plants grown at -3 kPa and the lowest yield per plant was obtained from the plants grown at -15 kPa. Our results were different from the findings of Bian *et al.* (2018); this may be due to the fact that water requirement of eggplant is increased when plants enter into the full fruit-bearing period. During that time, the water supply rates at a negative pressure irrigation of -8 and -15 kPa did not meet the normal growth requirements of the eggplant, thus yield is reduced. Meanwhile, it was observed that the water consumption from the full fruit-bearing period to the late growth stage accounts for a large proportion of water consumption during the whole growth period. Therefore, low irrigation pressure was not conducive to improve the water use efficiency of eggplant at -8 and -15 kPa.

Conclusion

In this study eggplants were grown under a stable negative pressure of -3 to -15 kPa. Negative pressure irrigation reduced the water consumption of eggplant by up to 20.51–70.00%, decreased the total water consumption intensity of plants by up to 22.18–70.27%, and increased the water use efficiency by 7.45 to 41.48%. Negative pressure irrigation also promoted the accumulation of dry matter of eggplant. When the irrigation pressure was maintained at -3 kPa, plant height, stem diameter, and dry weight of eggplant at the late growth stage was increased by up to 20.20, 23.81 and 12.71%, respectively compared with control. Similarly, the yield of eggplant was improved by 12.43% compared with control. Negative pressure irrigation (-3 kPa) also improved the nitrate reductase activity (6.14–15.50%), root activity (11.11–33.33%), and chlorophyll content (20.04–51.58%) of eggplant at different growth stages compared with control. The soluble sugar, soluble protein, and vitamin C contents of eggplant fruit were increased by 14.47–47.22%, 16.33–58.78%, and 19.64–43.42%, respectively, compared with control. The stable negative pressure irrigation (-3 kPa) reduced the water consumption and improved the water use efficiency. The stable negative pressure irrigation improves eggplant growth and development, improves the physiological activity, increases the yield, and improves the quality of eggplant.

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Author Contributions

All the authors declared that everyone contributed adequately to all the procedures of the experiment and manuscript writing. J.Z. conceived and designed the research, performed experiments and analyzed the data. J.Z. also participated in drafting the manuscript. P.W. designed the research and revised the manuscript critically for the main content. H.L. revised the manuscript critically for the main content. X.H. and J.S. analyzed the data. All authors approved the final manuscript for publication and agreed to be accountable for all aspects.

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