



The effects of different fertilizer rates on water and nitrogen transport characteristics in the wetted body of bubbled-root irrigation

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Abstract

Bubbled-root irrigation could transport water and fertilizer to roots of fruit trees effectively. In order to study the characteristics of water and nitrogen transportation in the wetting body, a field experiment was conducted in Yulin city, Shanxi. During the experiment, the total amount of 30 L irrigation with 7 L/h emitter flow rate was applied by a Markov bottle. The 3 fertilizer rates were 33.3, 41.7, and 50.0 g/L. The irrigation without fertilizer was as control. The results showed that infiltration capacity of bubbled-root irrigation increased with the fertilizer rate application increase. The horizontal and vertical wetting velocities of the vertical section increased with the fertilizer rate increase, and emerged a good power function relation with time. The wetting depth of wetting body in bubbled-root irrigation increased with the fertilizer concentration increase. The average moisture content distribution for all irrigation and fertilizer application treatments was similar, and the water content increased with the fertilizer concentration increase. The $NO_3^- - N$ and $NH_4^+ - N$ concentration at the same infiltration depth increased with the fertilizer solution concentration increase. After the water redistribution, the $NO_3^- - N$ and $NH_4^+ - N$ concentration at the 70-cm soil depth was close to that at the background. The effects of different nitrogen concentrations on conversion rate of soil were different, the conversion rate of nitrate was not significant, and the 33.3 g/L had the highest conversion rate of $NH_4^+ - N$.

Keywords Tinfiltration · Nitrogen · Bubbled-root irrigation · Fertilizer solution infiltration · Wetted body · Water and nitrogen distribution

Introduction

Bubbled-root irrigation is a water-saving irrigation technology for underground local irrigation by burying the irrigator at different soil depths. It can make the irrigation water directly into the depth of the soil, and affect the root system of fruit trees.

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Compared with the original drip irrigation method, it can greatly reduce the water consumption and ground evaporation loss due to the infiltration of water from the ground. It overcome the shortcomings of aboveground micro-irrigation and underground seepage irrigation, and realized the fundamental transformation from irrigated soil to irrigated crops (Liu and Jiang 2020; Wu et al. 2010; Zhang et al. 2016). The working principle of bubbled-root irrigation is to ensure the irrigation water be smoothly transported to the inside of the irrigation device with installing micro tubes with a 4-mm diameter on the capillary, and to level the end of the water inlet with 1 to 2 cm above the ground by inserting the micro tubes into the inlet of the bubbled-root irrigation water buried in the soil. Since the irrigation device is surrounded by a casing that is slightly larger than its diameter, the irrigation water flows out of the outlet through the energy dissipation in the flow channel, and then through the casing introduce the soil in the way of non-point source outflow for irrigation. Generally, the irrigator has a water outlet. After the irrigation water passes through the flow channel, it is irrigated from the water outlet to the soil, and the water

outlet is located inside the inner core to avoid direct contact between the water outlet and the soil. A vent overflow port is provided at the top of the irrigator, which is isolated from the water inlet and only communicates with the hollow inner side of the inner core. When the soil infiltration flow is greater than the irrigation flow, the overflow water pipe is only used for aeration. The water flow will be led to another wet area through the overflow hole through the gap between the irrigation device and the casing to continue irrigate after the water in the soil being saturated. The bubbled-root irrigation is equipped with different types of over-water flow channels, which improves the accuracy of flow control, in addition because the irrigator is provided with a protective sleeve to avoid clogging problems with the dripper, not only the materials and methods. It is relatively simple, and its service life has also been greatly improved, which has a more significant advantage than drip irrigation. The size and shape of the wet body under various irrigation technology conditions have a greater impact on the growth of fruit trees. Therefore, the research on the point source infiltration of the wet body is the basis of the research on the technical elements of root spring irrigation. There have been many studies on the characteristics of point source infiltration wetted body and water infiltration (Li et al. 2009a; Zhang 2020)). The research on the infiltration law of the wetting body is the basis for the research on the technical elements of bubbled-root irrigation and the coupling of water and fertilizer. Recent work has studied the root zone moist body of crops under drip irrigation and simulated the transport of water in soil by establishing the Hydrus model under drip irrigation conditions (Beggs et al. 2004; Ben-Asher et al. 1986; Bhatnagar and Chauhan 2008; Bristow et al. 2000; Cote et al. 2003; Patel and Rajput 2008; Skaggs et al. 2010). However, the study of bubbled-root irrigation has not yet been seen. Domestic scholars have conducted research on bubbled-root irrigation. For instance, Liu et al. (2016) showed that the depth of the Irrigation emitters emerged a greater influence on the transport distance of the wetting front by investigating the soil moisture and wetting front transport of bubbled-root irrigation under different irrigation depths. Fei et al. (2017) conducted infiltration experiments for bubbled-root irrigation under different soil bulk densities. The results showed that the moisture content and the distance of wetting front were negatively correlated with soil bulk density. Fan et al. (2011) reported that soil bulk density and initial moisture content had little effect on the shape of the wetting body. Li et al. (2012) applied HYDRUS3D software to simulate the soil water movement characteristics under the condition of bubbled-root irrigation. The results showed that there was a positive correlation between the characteristics of the wetting body and the flow. The greater the flow, the faster the transport speed of the wetting front and the higher the soil moisture content. Li et al. (2013) showed that the flow rate positively correlated with the water transport rate and negatively related to the volume of the wetting body using HYDRUS3D

software to simulate the water movement of the bubbled-root irrigation. The degree of open porosity affected the moisture distribution in the wetting body. Zhang et al. (2013) studied the effects of soil bulk density, initial water content, the height of the Irrigation emitters, and the depth of burial on soil infiltration in bubbled-root irrigation, and established a corresponding comprehensive prediction model. Li et al. (2009b) studied the infiltration of water under different bulk density conditions. The results showed that the infiltration capacity decreased with the increasing of soil bulk density, and the infiltration rate parameter increased with the increasing of soil bulk density. Liu et al. (2017) studied the soil moisture distribution and wetting front transport at the different initial soil moisture in bubbled-root irrigation under water-fertilizer coupling, and proposed the models for the transport distance of bubbled-root irrigation under different initial moisture content conditions.

In summary, studies on the law of soil water movement in bubbled-root irrigation have been extensively studied in China. However, most of these researches only focused on the movement of soil moisture in infiltration, the form of wetting body, and the transport rule of wetting front. The research on wetting body of bubbled-root irrigation under infiltration of fertilizer solution has not been documented. Thus, the objective of this study is to study the effects of infiltration of fertilizer solution on the characteristics, moisture content distribution, and nitrogen distribution of wetting body under different conditions, to establish the basis for water and fertilizer coupling in bubbled-root irrigation.

Material and methods

Research area

The experiment was conducted at the Micro-Irrigation Jujube Demonstration Base of Northwest A & F University in Mengcha Mountain, Mizhi County, Shaanxi, China. The topography of this area is hilly-gully of the Loess Plateau, and the climate is semi-arid. The average annual temperature and precipitation is 451.6mm and 612.3 mm (from 1971–2014). A total of 39%–64% of the average annual precipitation occurs between July and September. The soil type in this area is loessal soil, whose particle size ratios of <0.002, 0.002–<0.02, 0.02–<0.20, and 0.2–2.0 mm are respectively 17.55%, 42.59%, 38.86%, and 1.00%. The average bulk density of soil is 1.31 g/cm³, the initial soil moisture content is 10.4%, the soil field water-holding capacity is 23.4%, and the soil saturated moisture content is 39.8%. The available *N*, *P*, and *K* contents were respectively 34.739 mg/kg, 2.909 mg/kg, and 101.9 mg/kg, organic matter content was 0.21%, soil average $NO_3^- - N$ content was 12.63 mg/kg, and soil average $NH_4^+ - N$ content was 0.89 mg/kg.

Research device and experimental design

Bubbled-root irrigation system is composed of an irrigator and an irrigator casing. The bubbled-root irrigation test consists of water supply system and irrigation emitters. The structure and the section of the irrigator are shown in Fig. 1. The water supply system uses a Markov bottle made of rigid plastic with a cross-sectional area of 70.88 cm² for automatic water supply. Irrigation emitter volume was 30 L with a 7 L/h flow rate. The 3 fertilizer application rates were set as 33.3 g/L, 41.7 g/L, and 50.0 g/L, respectively. The fresh water was set as the control (the concentration of the fertilizer was 0 g/L). There is an air vent above the irrigation emitters communicated with the air. The flow rate is controlled by adjusting the knob at the bottom of the Markov bottle. The dripper flow is adjusted by stopwatch and a 20-ml cylinder, and the irrigation emitters' flow rate is checked by certain times during the test to ensure the water supply stability.

The height and outer diameter of bubbled-root irrigation emitters are 20 cm and 4 cm, respectively. The irrigation emitters and supporting sleeve are directly installed and removed through the screw hole. The size of matching sleeve (*PVC material*) wall was with 2-mm thickness, 4-cm inner diameter, and 4.4-cm outer diameter. A hole with 2-mm diameter and 20% opening degree is punched from the top to the bottom of the matching sleeve of the irrigation emitters at 2-cm intervals. The opening part of the hole is wrapped with gauze to prevent the soil particles from entering the Irrigation emitters and causing blockage. Figure 2 is a schematic diagram of the irrigation method of bubbled-root irrigation.

Test methods and observations

Select the original soil slope in the test area and make it a smooth terrace (2 m in height and 2 m in width), the vertical section is used as the observation plane, and the experimental system is shown in Fig. 3.

Cumulative infiltration is the total amount of water passing through a unit area over a certain period of time. It is determined by dividing the water supply of the Markov bottle (the cross-sectional area of the Markov bottle multiplied by the depth of the water supply scale) by the water seepage area of the emitter. Due to the particularity of the structure of the emitter, a certain amount of water will form in the casing under the bubbled-root irrigation, and the depth of the water will change with time in the initial stage of infiltration; consequently, the water seepage area of the emitter is a dynamic value that change with time. Assuming that the water volume of the Markov bottle is all supplied to the emitter, the water seepage area of the emitter is composed of the water seepage surface of the bottom of the water tank and the water seepage surface of the side of the casing, namely:

$$S = \pi r^2 + 0.2 \times 2\pi r h(t) \tag{1}$$

In the formula, the casing radius of the emitter is the depth of water accumulated in the casing of the emitter during different infiltration times, mm.

The cumulative infiltration curve under different fertilizer concentrations is described by the Kostiakov infiltration model in the following form:

$$Z = Kt^\alpha \tag{2}$$

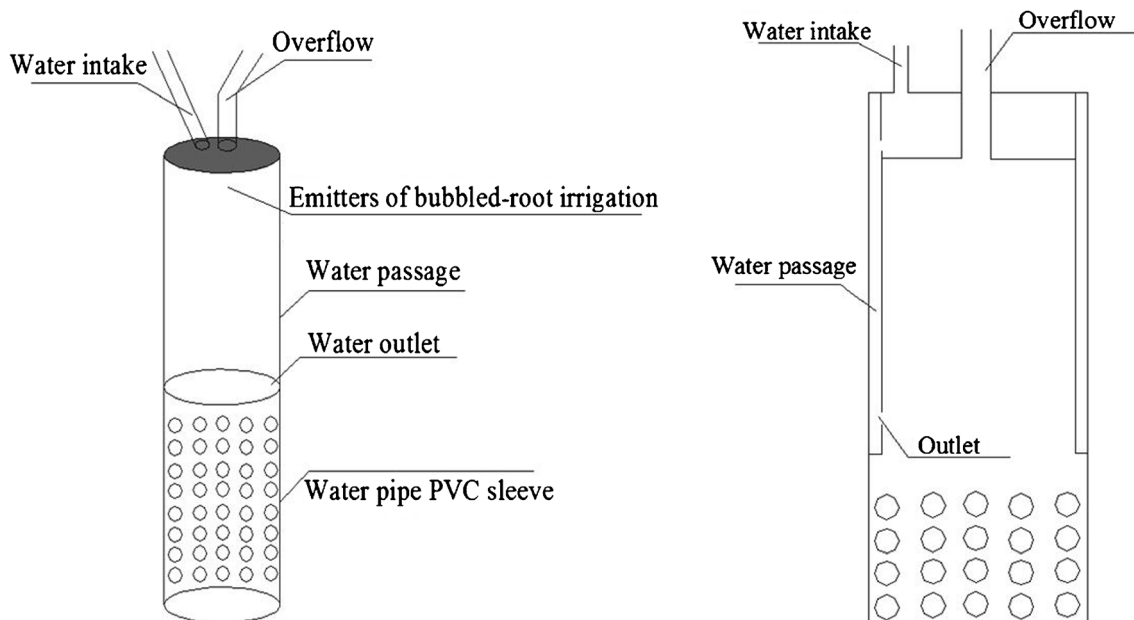


Fig. 1 Schematic diagram of structure and section of irrigation device of bubbled-root irrigation

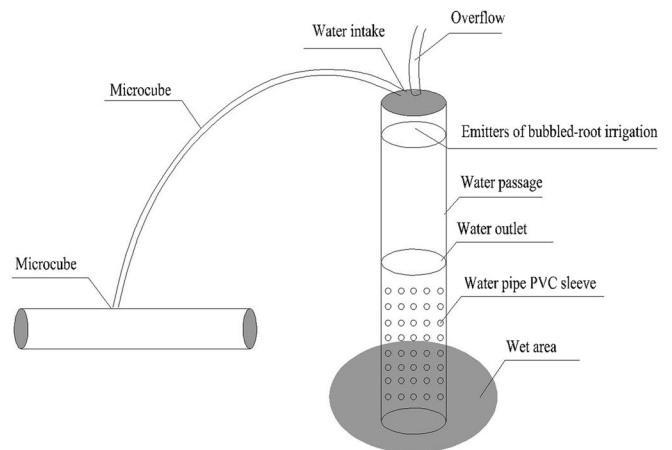
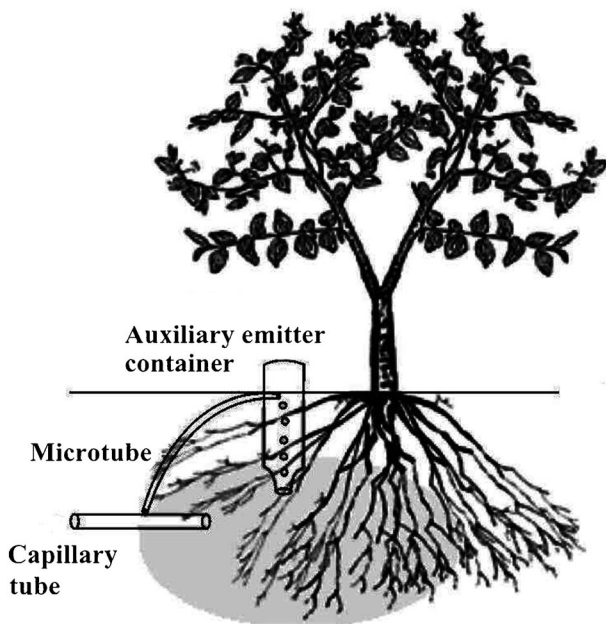


Fig. 2 The schematic diagram of the irrigation emitters

In the formula, Z is the cumulative infiltration of the infiltration of the bubbled-root irrigation fertilizer, mm; K is the infiltration coefficient, $\text{mm}/\text{min}^\alpha$; α is the infiltration index, no unit; t is the infiltration time, min.

The infiltration rate is the amount of water passing through a unit area in a unit time period, which is determined by the cumulative infiltration amount divided by the infiltration time. The infiltration time is determined by a stopwatch with an accuracy of 0.01 s. The wet front migration distance at different time is directly measured with a steel tape measure on the test section. The soil moisture content was obtained by the

drying method, and the soil moisture content was measured at different time intervals every 10 cm in the vertical depth range of 0 to 100 cm. In the infiltration stage and the redistribution process, three repetitions were made to avoid the accuracy of water content measurement at the same position during the redistribution process. The water content data were averaged. The soil ammonium and nitrate nitrogen content were measured using a fully automatic discontinuity chemical analyzer (Analyzer model: *CleverChem200*). In order to reduce the influence of rainfall and evaporation on the wetting body, the wetting body was covered with a plastic cloth after the test. Three replicates of each group were tested and their mean value was taken as the test result.

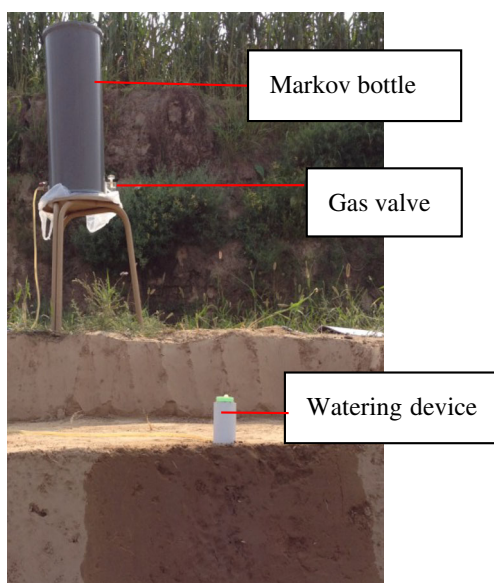


Fig. 3 Experimental system structure

Data analysis

Excel 2007 was used to process test data and plots, and SPSS 11.5 software was used for statistical analysis, and related indicators were analyzed for significance. The significance level was ($P < 0.05$), and the extremely significant level was ($P < 0.01$).

Result and discussion

The effect of fertilizer rates on infiltration capacity of bubbled-root irrigation

Figure 4 shows the dynamic change curve of the cumulative infiltration volume of bubbled-root irrigation at different fertilizer solution concentrations when the dripper flow is 7 L/h and the irrigation volume is 30 L. The cumulative infiltration

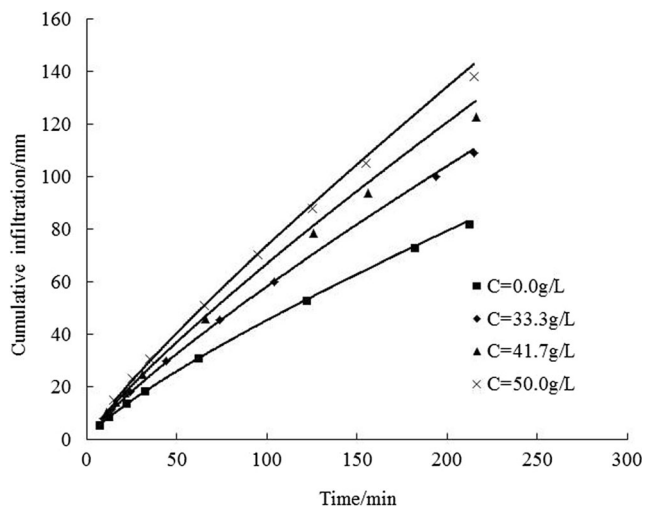


Fig. 4 Cumulative infiltration curve under bubbled-root irrigation fertilizer solution infiltration

volume of clean water and fertilizer solution infiltration in bubbled-root irrigation shows an increasing trend under the same infiltration condition. From the beginning of infiltration about 20 min, the differences of cumulative infiltration volume of 33.3 g/L and 41.7 g/L were not significant. The difference of the cumulative infiltration of 41.7 g/L and 50.0 g/L was significant. With the infiltration time increasing, the difference between different rates was more pronounced. At the same time, the cumulative infiltration of fertilizer solution infiltration is greater than the cumulative infiltration quantity of infiltration of clear water, indicating that the concentration of fertilizer solution has a great influence on the infiltration capacity of soil. Both horizontal and vertical have a solute potential under the infiltration of fertilizer solution, so that the infiltration amount and infiltration rate of fertilizer solution infiltration are greater than infiltration of clear water. The infiltration amount increases with the increasing of the infiltration fluid concentration.

The infiltration rate decreases with the time, and the infiltration rate of fertilizer solution is greater than the infiltration rate of clear water infiltration; the infiltration rate of fertilizer solution infiltration was faster than the clear water, and the infiltration of fertilizer solution infiltration on the infiltration of bubbled-root irrigation was more significant. The cumulative infiltration and infiltration rate showed a smooth and continuous curve during the entire infiltration process with infiltration time.

The cumulative infiltration corresponding to different infiltration levels at different fertilizer levels was analyzed using Person analysis is shown in Table 1.

Table 1 showed that the relationship between the concentration of fertilizer solution and the infiltration amount at different times is different. The cumulative infiltration and infusion concentration are not significant between the infiltration time within 7 min; however, the correlation coefficient

increased with the increasing of infiltration time. It manifests that with the infiltration time, correlation between cumulative infiltration and fertilizer concentration is more significant ($P < 0.05$). It shows that the cumulative infiltration increases with the increasing of fertilizer concentration.

The measured data of accumulated infiltration volume of bubbled-root irrigation fitted with *Kostiakov* model (Formula (2)); the fitting result is as follows:

$$\text{Clear water } C = 0 : Z = 1.171t^{0.804}, R^2 = 0.999 \quad (3)$$

$$\text{Concentration } C = 33.3 \text{ g/L}, Z = 1.243t^{0.826}, R^2 = 0.986 \quad (4)$$

$$\text{Concentration } C = 41.7 \text{ g/L}, Z = 1.301t^{0.841}, R^2 = 0.997 \quad (5)$$

$$\text{Concentration } C = 50.0 \text{ g/L}, Z = 1.443t^{0.863}, R^2 = 0.998 \quad (6)$$

Take the significance level was 0.01, and R^2 was greater than the critical correlation coefficient r_α (0.6055), indicating that the relationship between the cumulative infiltration volume of bubbled-root irrigation infusion solution and the time can be fitted by *Kostiakov* model.

Under the bubbled-root irrigation, the cumulative infiltration of soil with increased with the increasing of fertilizer solution concentration. Because of the loose soil texture, a large number of non-capillary pores and capillary pores were distributed. In the early infiltration period, the free infiltration stage is mainly filled with water in the pores of the non-capillaries. The difference in the infiltration volume of fertilizer solution was not significant in the first 20 min. When the infiltration time lasts to more than 20 min, the difference of infiltration volume in different concentration of fertilizer solution was significant, which means that the pore water-holding capacity of the capillary tube reaches the maximum, and the rest was non-capillary pores. The size of the non-capillary pores determines the aeration and permeability of the soil, and the soil has reached near saturation or already. In the saturated state, the infiltration amount is basically linear with time, and the urea solution effectively improves the distribution of soil aggregates, especially the water-stable aggregates in the non-capillary pores. The infiltration rate increased due to the formation of better ventilation and water permeability in the pores (Guo et al. 2017; Lv et al. 2013). It resulted in increment of cumulative infiltration during the corresponding period of time.

Through analysis, it was found that the infiltration coefficient K , the infiltration index α , and the fertilizer solution concentration C showed a linear relationship, that is:

$$K_c = uC + k_0 \quad (7)$$

$$\alpha_c = vC + \alpha_0 \quad (8)$$

In the formula, K_c , α_c —infiltration coefficient, infiltration index of the fertilizer solution; u , v —fitting coefficient; and k_0 , α_0 —infiltration coefficient of clean water, infiltration index.

Table 1 Correlation between concentration of fertilizer solution and infiltration volume corresponding to different infiltration times

		Correlation coefficient	Fertilizer concentration	Infiltration time/min			
				7	35	125	215
Fertilizer concentration		<i>r</i>	1				
Infiltration time/min	7	<i>r</i>	0.566	1			
	35	<i>r</i>	0.880**	0.952	1		
	125	<i>r</i>	0.880**	0.964*	0.840**	1	
	215	<i>r</i>	0.978**	0.957**	0.857**	0.953**	1

** Correlation is significant at the 0.01 level

*Correlation is significant at the 0.05 level. The same as below

And perform linear regression analysis is :

$$K_c = 0.005C + 1.171, R^2 = 0.944 \tag{9}$$

$$\alpha_c = 0.001C + 0.804, R^2 = 0.982 \tag{10}$$

Substitute Eqs. (9) and (10) for the infiltration parameters K_c and α_c regression equation into Eq. (2) to obtain the cumulative infiltration per unit area with the time in bubbled-root irrigation at different fertilizer solution concentrations. The quantity model is:

$$Z = (0.005C + 1.171) t^{(0.001C+0.804)} \tag{11}$$

To verify the reliability of Eq. (11), this model was used to calculate the cumulative infiltration volume per unit area of infiltration of bubbled-root irrigation fertilizer solution with a concentration of 50 g/L. Table 2 shows the fitting results.

According to Table 2, the relative deviation between the calculated and measured values of the model ranged -3.38 to 5.38%, and the relative deviation is less than ±6%, which indicates that using Formula (11) to calculate the cumulative infiltration volume per unit area of bubbled-root irrigation is reliable.

The effect of fertilizer concentration on wetting front transport

Figure 5 shows the curve of the transport of the wetting front over time in the vertical section of the bubbled-root irrigation with different irrigation solution concentrations under the 30 L

irrigation volume and 7 L/h dripper flow rate. It can be seen that both the horizontal and vertical wetting front transport distances have a significant positive correlation with the fertilizer solution concentration. The horizontal and vertical wetting front transport distances increase with the infiltration time.

The correlation analysis of the wetting front transport distance corresponding to the infiltration time in the horizontal direction and the vertical direction of different fertilizer solution levels was analyzed using the *Person* analysis method, as shown in Table 3.

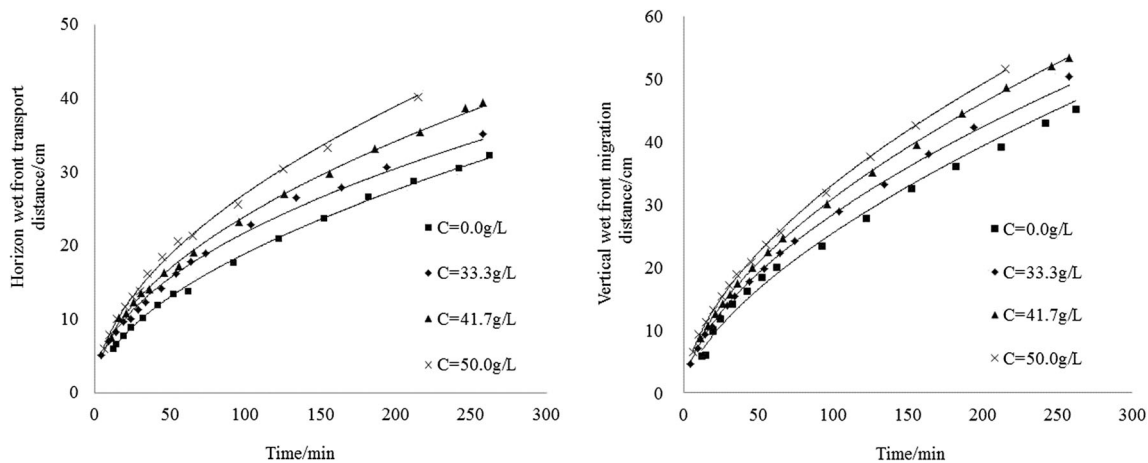
The relationship between the different concentration of fertilizer solution with time corresponding was different at the distance of vertical wetting front transport and horizontal direction. There was no significant difference between fertilizer concentration and horizontal and vertical wetting front transport distances in 7 min of infiltration time, and the correlation coefficient increased with the increasing of infiltration time. It shows that significant correlation could be found between the concentration of fertilizer solution than horizontal and vertical wetting front transport distances with the infiltration time ($P < 0.05$). It manifests that the horizontal and vertical wetting front transport distances increase with the increasing of fertilizer concentration.

According to the analysis, the distance between the infiltration of fertilizer solution in the horizontal direction and the vertical direction under the condition of bubbled-root irrigation fitted a power function relationship with time t , namely:

$$R_{(x,z)} = At^b \tag{12}$$

Table 2 Comparison of simulated and measured values on cumulative infiltration by the model

Project	Infiltration time/min							
	15	25	35	65	95	125	155	215
Measured value/mm	15.15	23.14	30.60	51.15	70.09	88.01	105.22	138.05
Calculated/mm	14.37	22.33	29.85	50.91	70.63	89.50	107.74	142.88
Relative deviation/%	5.38	3.64	2.51	0.46	-0.77	-1.66	-2.34	-3.38



(a) Wetting front transport in horizontally direction

(b) Wetting front transport in vertically direction

Fig. 5 Variation of wetting in vertically profile

In the formula, $R_{(x,z)}$ —the wetting front transport distance in the horizontal (vertical) direction of bubbled-root irrigation, cm; A , b —the fitting parameters. Using Eq. (12) to fit the horizontal and vertical wetting front transport distance data in Fig. 5, the relationship between the transport distance and the infiltration time of the soil infiltration wetting front is shown in Table 4.

Better fitting results could be found for the parameters of the wetting front transport distance in different directions by the power function model. Both of the correlation coefficients were greater than 0.96, and all are greater than the critical value when the significance level is $r_{\alpha}=0.01$. There is a significant relationship between the transport distance of horizontal wetting front and vertical wetting front in bubbled-root irrigation infiltration process.

The A and b parameters have a single variation with the increasing of fertilizer concentration. Thus, a linear correlation analysis is used to analyze the correlation

between parameters A and b and the concentration of fertilizer solution.

Parameter A :

$$\begin{cases} A(C)_x = 1.316 + 0.016C & R^2 = 0.934 \\ A(C)_z = 1.361 + 0.015C & R^2 = 0.937 \end{cases} \quad (13)$$

Parameter B :

$$\begin{cases} b(C)_x = 0.573 - 0.001C & R^2 = 0.913 \\ b(C)_z = 0.632 - 0.001C & R^2 = 0.933 \end{cases} \quad (14)$$

According to Eqs. (13) and (14), there was a good linear relationship between the parameters and the concentration of fertilizer solution. The change of parameter b in the range of concentration in Eq. (14) has little effect, so the coefficient can be ignored. Retention of constant and substitute it into Eq. (12), a simplified mathematic model was constructed of horizontal and vertical wetting front migration distances with

Table 3 Correlation analysis of horizontal wet front and vertical wet front

Correlation coefficient		Horizontal direction				Vertically direction							
		Fertilizer concentration	Time/min			Fertilizer concentration	Time/min						
			7	35	125		215	7	35	125	215		
Fertilizer concentration	r	1				1							
Time/min	7	r	0.526	1		0.799**	1						
	35	r	0.927**	0.607*	1	0.974**	0.836**	1					
	125	r	0.949**	0.662*	0.997**	1	0.992**	0.777*	0.988**	1			
	215	r	0.917**	0.586*	0.999**	0.995**	1	0.955**	0.764*	0.991**	0.983**	1	

Table 4 Fitting result of wetting front transport distance in vertical profile

Conditions		Fitting equation	A	b	R ²
Horizontal direction	0 (clear water)	$R=1.362t^{0.575}$	1.362	0.575	0.962
	33.3g/L	$R=1.731t^{0.551}$	1.731	0.551	0.992
	41.7g/L	$R=1.910t^{0.550}$	1.910	0.550	0.970
	50g/L	$R=2.225t^{0.549}$	2.225	0.549	0.988
Vertical direction	0 (clear water)	$R=1.410t^{0.629}$	1.410	0.629	0.994
	33.3g/L	$R=1.743t^{0.612}$	1.743	0.612	0.999
	41.7g/L	$R=1.981t^{0.599}$	1.981	0.599	0.977
	50g/L	$R=2.242t^{0.589}$	2.242	0.589	0.993

time under conditions of fertilizer solution infiltration in the bubbled-root irrigation:

$$\begin{cases} R(t, C)_x = (1.316 + 0.016C)t^{0.573} \\ R(t, C)_z = (1.361 + 0.015C)t^{0.632} \end{cases} \quad (15)$$

where $R(t, C)_x$, $R(t, C)_z$ —the transport distance of the horizontal (vertical) moist peak with time under the conditions of bubbled-root irrigation with different fertilizer concentrations, *cm*.

In order to verify the accuracy of Eq. (15), this model was used to fit the transport distance of bubbled-root irrigation infusion solution with a concentration of 50.0 g/L in the horizontal direction and in the vertical direction. The fitting results are shown in Table 5.

According to Table 5, the relative deviation between the measured value and the fitted value of the wetting front transport distance in the horizontal and vertical directions is ±7%. The wetting front transport distance prediction on vertical profile of bubbled-root irrigation was improved by adopting the modified Eq. (15), and satisfied the accuracy requirements.

The effect of fertilizer concentration on dynamic distribution of moisture content of infiltration wetting body of bubbled-root irrigation infusing solution

Figure 6 shows the soil moisture content of bubbled-root irrigation in clear water and different fertilizer concentrations at

the end of irrigation after 1-day and 3-d redistribution. CK is the initial soil moisture content. The water distribution patterns of infiltration soil are similar with different fertilizer concentrations of bubbled-root irrigation. At the end of irrigation, the soil moisture content is 27% in the surface layer (0~30 cm), and the soil moisture content is 26.23% in the middle layer (30~60 cm), and 14.79% in the bottom layer (60~100 cm). The soil moisture content in surface layer and the middle layer are significantly higher than the bottom layer. The surface layer is slightly higher than the middle layer. After 1-day distribution, the soil moisture distribution moved downward from the surface layer, and showed the trend of low surface (18.1%), medium high (19.96%), and low bottom (14.93%), respectively. After 3 days of redistribution, the soil moisture content changed significantly. The average soil moisture content in 0–60-cm layer was 9.4% lower than that at the end of irrigation.

The distribution law of the average soil water content with clear water and different fertilizer concentrations remained similar in bubbled-root irrigation, and the fertilizer solution infiltration affected the soil moisture distribution. The soil moisture content in the same soil depth increases with the increasing of fertilizer concentration in a certain fertilizer concentration range. This resulted from the solute transport with moisture. There was a more granule structure that formed in the soil with the increasing of fertilizer solution concentration, which increases the porosity of surface soil and resulted in the

Table 5 Comparison of simulated and measured values on wetting front transport by the model

Transport distance		Infiltration time/min							
		15	25	35	65	95	125	155	215
R_x	Measured value/mm	10.03	13.00	16.10	21.30	25.60	30.40	33.30	40.10
	Calculated/mm	9.54	12.67	15.28	21.55	26.62	31.00	34.94	41.91
	Relative deviation/%	5.17	2.61	5.39	-1.17	-3.81	-1.94	-4.70	-4.33
R_z	Measured value/mm	11.30	15.40	18.90	25.60	31.90	37.60	42.70	51.60
	Calculated/mm	10.92	14.89	18.27	26.60	33.49	39.57	45.08	54.99
	Relative deviation/%	3.44	3.39	3.45	-3.77	-4.76	-4.97	-5.29	-6.16

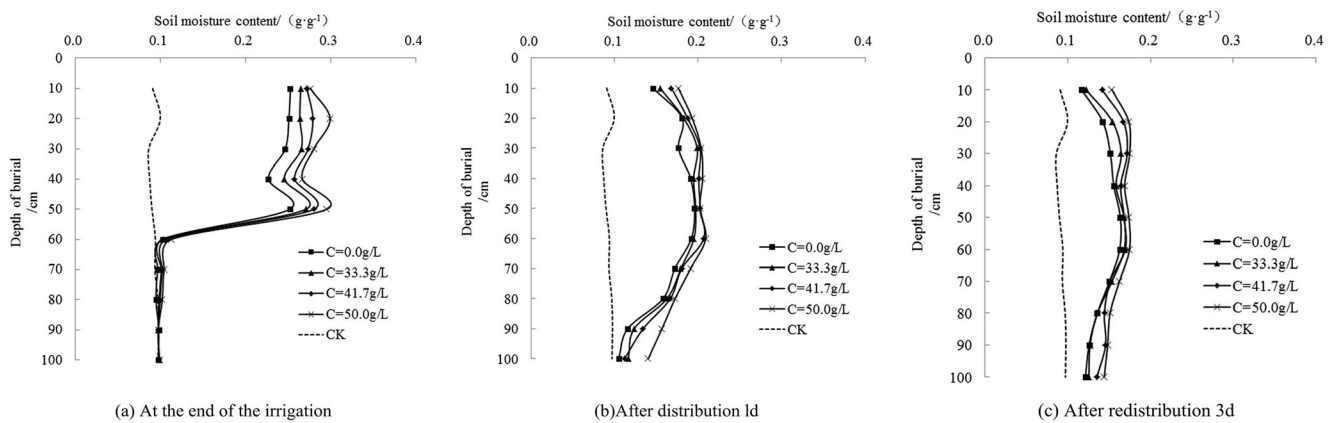


Fig. 6 Variation of vertical soil water content at irrigation emitters in different fertilizer concentrations

soil moisture content of different soil depths increases with the increasing of fertilizer concentration. After 3 days of redistribution, the differences in water content distribution of soil layers treated decreased with different fertilizer concentrations gradually. From the results of the infiltration stage, it can be seen that the infiltration stage of the fertilizer solution increases the total and non-capillary pores, and the water-conducting flow as the capacity increases. The number of water-stable aggregates increases significantly, therefore, the infiltration volume increases with the increasing of fertilizer concentration. The redistribution stage of soil water is actually the dynamic process in which water in the pores of the soil is transformed into empty water. According to the soil characteristics, the soil pores in the dewetting state generally become empty in the order from large to small, of which most of the macropores are composed of non-capillary pores; therefore, the aquifer's ventilatory ability and [water transmitting ability](#) translate the drainage capacity in the redistribution stage. The greater the concentration of fertilizer solution, the stronger the drainage capacity of non-capillary pores in the redistribution phase. Opposite, when the concentration of fertilizer solution is small, the pores in the redistribution stage have a low amount of pores and the drainage capacity is weak. The drainage rate of the soil is slower and the drainage is less in the same redistribution time. Therefore, the water content distribution in the fertilizer solution concentration is not as obvious as the distribution of moisture content in the infiltration stage when the redistribution reaches a certain time.

Figure 6 shows the analysis of variance of the distribution on soil moisture content under the condition of fertilization irrigation. The results are shown in Table 6.

Analysis of variance showed that the change law of moisture content within the depth of 0~100 cm varied with observation time, and there was a significant difference within 3 days ($P < 0.05$). The concentration of fertilizer solution had no significant effect on the change of water content at 80~100 cm ($p > 0.05$), and the more obvious the effect on the law of water content

change with the greater the depth. In order to further analyze the change process of water influence, the change of water content and relative change rate are compared respectively, that is, the water change at 0~70 cm is averaged, and the average value of water under different fertilizer concentration is compared at the end of irrigation. The change of water content at 3 days redistribution analysis showed that the change of water content under the treatment of each fertilizer concentration was the following: -0.25 g/g (33.3 g/L), -0.24 g/g (50.0 g/L), and -0.23 g/g. (33.3 g/L); the relative change rate of water content is the following: 31.6% (33.3 g/L), 31.5% (50.0 g/L), and 29.4% (41.7 g/L) of the above comparison results. The effect of reducing water reduction at 0~70cm is suitable for the concentration of fertilizer solution 41.7 g/L, which can better ensure the water absorption of jujube roots.

The effect of fertilizer concentration on the transport characteristics of infiltration NO_3^- -N in bubbled-root irrigation infusing solution

Figure 7 showed the concentrations of NO_3^- -N in the soils at the end of irrigation and after redistribution 1 day. The content of NO_3^- -N increased with the concentration of the leachate at the same depth in the soil layer, and reaches the maximum at the 20~40-cm soil depth. During the irrigation process, the fertilizer solution migrated with the water. At the end of irrigation, the surface NO_3^- -N was slightly higher than that in the middle layer of soil. After redistribution 1 day, NO_3^- -N migrated downward with the water from the surface layer, showing the change trend of the low surface level and high middle level. The law of transport is similar to that of soil moisture. This could be explained by a negative charge of NO_3^- -N which was not easily retained by the soil colloids (Chen et al. 2018; Dong et al. 2006; Li et al. 2002). After redistribution 1 day, the content of NO_3^- -N in each soil layer increased. The NO_3^- -N content increased with the greater the concentration

Table 6 Distribution of water content for each layer under different fertilizer solution concentrations

Measurement time/day	Fertilizer concentration/(g·L ⁻¹)	Soil moisture content/(g·g ⁻¹)				
		0~20 cm	20~40 cm	40~60 cm	60~80 cm	80~100 cm
0 (end of irrigation)	33.3	26.4	25.5	18.7	10.0	9.8
	41.7	27.5	26.5	19.4	10.1	9.8
	50.0	28.7	27.3	20.4	10.3	9.8
1 (after redistributing 1 day)	33.3	16.9	19.7	19.6	17.1	12.0
	41.7	17.8	20.2	20.5	17.4	12.3
	50.0	18.5	20.5	20.6	18.2	14.9
3 (after redistributing 3 days)	33.3	13.8	16.1	16.8	14.5	12.6
	41.7	15.4	16.8	17.9	14.8	14.0
	50.0	16.4	17.2	17.4	15.7	14.6
Variance analysis	Fertilizer concentration	*	*	*	*	NS
	Redistribution time	*	*	*	*	*

of fertilizer solution. At the same depth, this is mainly because the soil contains a lot of NH_4^+-N after the infiltration of fertilizer solution. With the passage of time, nitrification becomes more vigorous under the right conditions, which makes the content of $NO_3^- -N$ increase significantly. In the surface soil, the ventilation conditions and temperature are relatively appropriate. The nitrification is stronger, which makes the content of $NO_3^- -N$ in surface soil the highest. The content of $NO_3^- -N$ decreases in the deeper soil depth, and tends to the background value (CK) at the depth of 70 cm.

Figure 7 shows the analysis of variance of the distribution of nitrate nitrogen in soils under the conditions of fertilizer irrigation. The results are shown in Table 7.

The above analysis of variance showed that the influence of soil nitrate nitrogen distribution on each layer tends to decrease with the buried depth increases regardless of fertilizer concentration or redistribution time, and the variance changes at 0~20 cm are more significant with concentration and time.

This is due to the shallow depth of 0~20 cm on the surface, and the distribution of soil pores is relatively intact, resulting in good aeration of the soil and high oxygen content, which provides a good ventilation environment for nitrification and conducive to nitrification. The nitrification was more obvious with the greater concentration of fertilizer solution, resulting in greater influence of fertilizer solution concentration on the difference of nitrate nitrogen content. Due to the poor soil ventilation conditions at 20~100 cm, the anaerobic environment is conducive to the denitrification and the denitrification is gradually enhanced with the increasing of the buried depth.

The effect of fertilizer concentration on transport characteristics of infiltration NH_4^+-N in bubbled-root irrigation

Figure 8 shows the distribution of NH_4^+-N in the depth direction of each soil layer after the end of irrigation and after

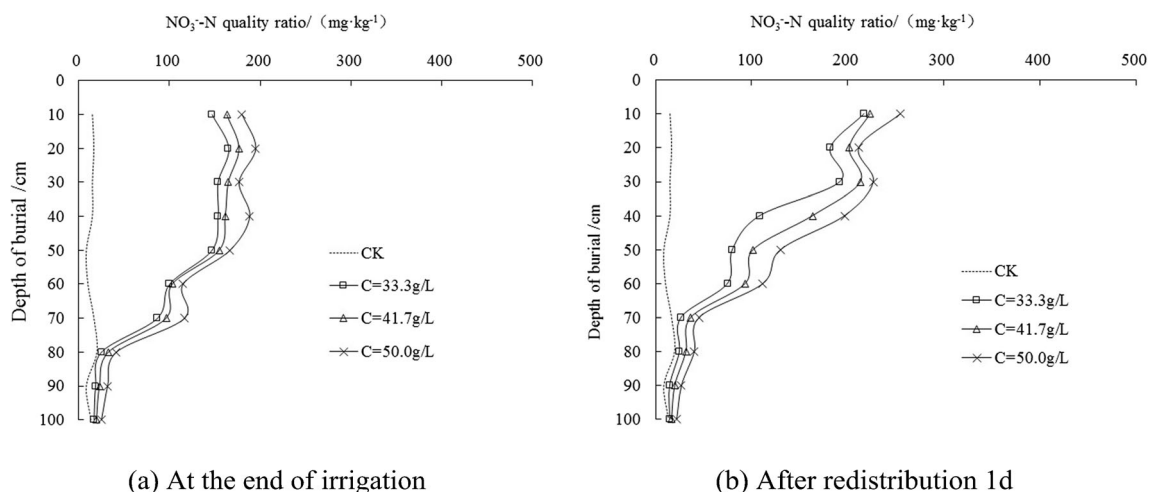
**Fig. 7** $NO_3^- -N$ distribution status under fertilizer solution infiltration of bubbled-root irrigation

Table 7 Distribution of water nitrate nitrogen content for each layer under different fertilizer solution concentrations

Measurement time/day	Fertilizer concentration/(g·L ⁻¹)	Nitrate nitrogen ratio in soil/(mg·kg ⁻¹)				
		0~20cm	20~40cm	40~60cm	60~80cm	80~100cm
0 (end of irrigation)	33.3	311.7	306.7	246.7	111.7	35.0
	41.7	340.0	326.7	258.3	130.0	43.3
	50.0	375.0	365.0	281.7	158.3	56.7
3 (after redistributing 3 days)	33.3	398.3	300.0	155.0	51.7	33.3
	41.7	425.0	376.7	195.0	68.3	36.7
	50.0	466.7	423.3	241.7	85.0	43.3
Variance analysis	Fertilizer concentration	*	NS	NS	NS	NS
	Redistribution time	*	NS	NS	NS	NS

redistribution of irrigation. CK is background value of NH_4^+-N . It can be seen that there is a significant positive correlation between the NH_4^+-N content and the infiltration fertilizer concentration at different soil depths, and the NH_4^+-N content was represented as the distribution of surface and middle high (0~60 cm) and the bottom low (60~100 cm) at the end of irrigation, and the more obvious the law increasing with the concentration of fertilizer solution. This is mainly due to the large amount of hydrolysis of urea in fertilizer solution during the infiltration test process to produce NH_4^+-N . Because of its transport being affected by the adsorption capacity of the soil to NH_4^+-N , the positively charged NH_4^+ is adsorbed by the negatively charged soil colloid, leading to a decrease in the content of NH_4^+-N in the infiltration solution. The diffusion of NH_4^+-N is hindered. This obstruction increases with the increasing of fertilizer concentration, so the NH_4^+-N content in the surface soil reaches the maximum. However, as the soil-adsorbed NH_4^+-N content became saturated, some NH_4^+-N continued to migrate downward under the effect of water flow. During the redistribution process, there is no further supply of fertilizer solution, the hydrolyzed NH_4^+-N

gradually decreased, and with the presence of free NH_4^+-N in the solution, the further hydrolysis of urea was inhibited, resulting in hydrolysis of the rate reduction. In addition, the NH_4^+-N 's ability to move with the water stream decreases with increasing soil depth. This is because the closed pores produced during the infiltration of fertilizer solution will cause an anaerobic environment, the internal ventilation of the soil will be weakened, and the nitrification reaction will be promoted. Therefore, the NH_4^+-N gradually decreases as the soil depth increases. With the change of burial depth, the effect of redistribution time on the distribution of soil NH_4^+-N was not significant in every layer, but was significant between 0 and 70 cm. The effect of redistribution time on the change law of NH_4^+-N gradually decreased.

Figure 8 shows the distribution of ammonium nitrogen content in all soil layers under the condition of fertilized irrigation. The results are shown in Table 8.

The above analysis of variance indicated that the effect of redistribution time on the distribution of soil NH_4^+-N at 0~100 cm was significant compared with moisture. And the effect of the change rule of NH_4^+-N content with the change

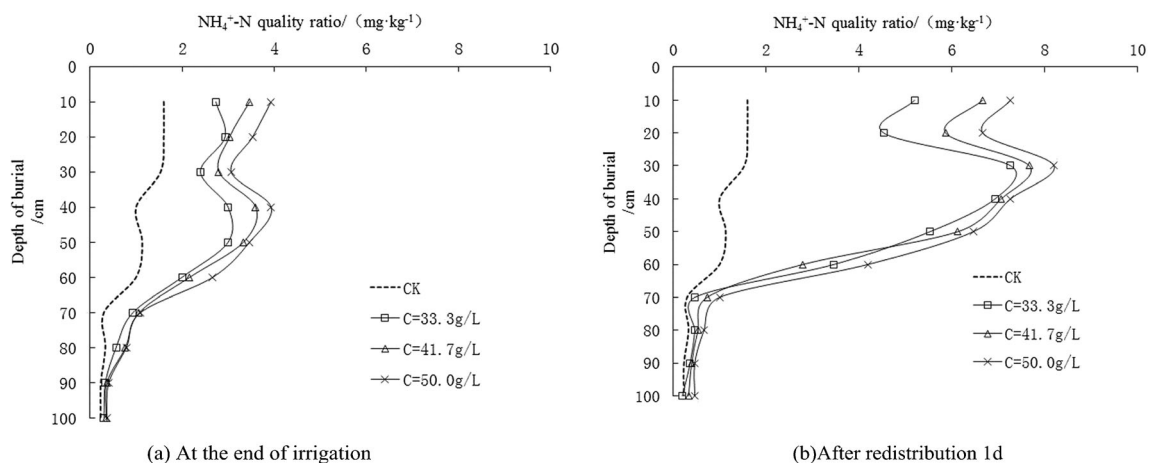


Fig. 8 NH_4^+-N distribution status under bubbled-root irrigation fertilizer solution infiltration

Table 8 Distribution of ammonium nitrogen content for each layer under different fertilizer solution concentrations

Measurement time/day	Fertilizer concentration/(g·L ⁻¹)	Fertilizer concentration/(mg·kg ⁻¹)				
		0~20cm	20~40cm	40~60cm	60~80cm	80~100cm
0 (end of irrigation)	33.3	5.67	5.40	5.00	1.50	0.64
	41.7	6.50	6.40	5.50	1.83	0.72
	50.0	7.47	7.00	6.13	1.89	0.77
3 (after redistributing 3days)	33.3	9.73	14.20	9.00	0.93	0.57
	41.7	12.53	14.73	8.93	1.27	0.73
	50.0	13.93	15.47	10.67	1.67	0.93
Variance analysis	Fertilizer concentration	NS	*	NS	NS	NS
	Redistribution time	*	*	*	NS	NS

of depth was gradually reduced. The significant differences were mainly concentrated at 0~60 cm, and the difference was significant within 3days ($P<0.05$). However, the significant effect of fertilizer solution concentration on the change of ammonium nitrogen concentration was only at 20~40 cm ($P<0.05$). The impact of other buried depth on ammonium nitrogen was not significant ($P<0.05$). This was mainly due to the water depth of the irrigation emitter outlet being 15cm from the surface; after the hydrolysis of fertilizer solution, the fertilizer solution infiltrates into the soil at the outlet of the irrigation emitters. The concentration of ammonium nitrogen in the vicinity of the outlet (20cm) increased as the concentration of fertilizer solution increases, and the degree of increase is more pronounced (redistribution 3days) with the change of time. This is because the adsorption capacity of NH_4^+-N to soil particles was improved, as most of them were fixed by soil and no longer moved downwards, resulting in a high concentration of NH_4^+-N measured near the dripper. By comparing the changes in the profile contents of ammonium nitrogen and nitrate nitrogen over time, it was found that the contents of ammonium nitrogen and nitrate nitrogen were almost close to the background value at a height below 70 cm, regardless of the concentration of fertilizer solution. For the purpose of water absorption and biomass accumulation effect of jujube root system, the average nitrogen conversion $NO_3^- - N$: -1.4% (33.3g/L) $< 0.1\%$ (41.7g/L) $< 0.1\%$ (50.0g/L) at 3days after irrigation at the depth of 0~70cm compared with that at the end of irrigation. NH_4^+-N : 94.5% (50.0 g/L) $< 96.7\%$ (41.7 g/L) $< 104.9\%$ (33.3 g/L); with the increase of fertilizer solution concentration, the average nitrate nitrogen conversion in 0~70 cm is due to the amount of irrigation water, must be a certain degree of inhibition of the nitrate nitrogen conversion rate, but did not change significantly, and ammonium nitrogen with the concentration increased, leading to 0~70-cm depth of less than ammonium nitrogen concentration decreases, with 50.0 g/L deal with ammonium nitrogen conversion rate under the condition of the lowest; 33.3 g/L processing under the condition of ammonia nitrogen conversion rate is the highest.

Conclusions

(1) Fertilizer infiltration conditions have a significant effect on water infiltration of bubbled-root irrigation. The cumulative infiltration and infiltration rates of fertilizer solution are greater than that of clear water, and the concentration of fertilizer solution has a significant positive correlation with infiltration capacity. The relationship between cumulative infiltration and infiltration time is in accord with the *Kostiakov* model. The horizontal and vertical wetting front transport velocities increase with increasing fertilizer concentration in the vertical section, and both have a good power function relationship with time and have significant correlation.

(2) The interaction between water movement and solute transport. The cumulative infiltration volume of bubbled-root irrigation increased with the increasing of fertilizer concentration, and the soil moisture content was also higher at the same position. At the end of irrigation, the distribution of moisture content was surface high (27%) and bottom low (14.79%) under the effect of water potential gradient. After 1-day distribution, the distribution of soil moisture began to migrate downward from the surface layer and showed the trend of surface low (18.1%), middle high (19.96%), and bottom low (14.93%). After 3 days of water redistribution, the average soil water content within 0–100cm was 6.34% lower than that at the end of irrigation. The distribution law of average water content in the soil of bubbled-root irrigation with clean water and different fertilizer concentration is similar. The water content of the same soil depth increases with the increasing of fertilizer concentration.

(3) The contents of $NO_3^- - N$ and NH_4^+-N at the depth of the same soil layer in bubbled-root irrigation had a significant positive correlation with the concentration of fertilizer solution under certain fertilization conditions. The distribution of $NO_3^- - N$ is similar to that of water movement; the distribution of $NO_3^- - N$ shows the change trend of the surface high and the middle low at the end of irrigation. After redistribution, $NO_3^- - N$ migrates from the surface to the surface with water,

and shows the change trend of low surface low and the middle high. NH_4^+-N content shows the distribution law of surface high and bottom low at the end of irrigation, but after redistribution, the content of surface NH_4^+-N increases to varying degrees. The content of NH_4^+-N in each soil layer gradually decreases with the increasing of depth of burial depth. After the redistribution, the contents of NO_3^--N and NH_4^+-N were close to the background value at a depth of 70 cm.

(4) With the maximum goal of root water absorption and biomass accumulation, variance analysis was conducted on the dynamic distribution of water and fertilizer in bubbled-root irrigation, and the water retention effect was better under the treatment of 41.7 g/L fertilizer concentration. Under this condition, the water absorption and biomass accumulation in the root of jujube tree at a depth of 0~70 cm could be better guaranteed. When the concentration of fertilizer solution reached 50.0 g/L, ammonium nitrogen transformation was inhibited instead, and the conversion rate reached the lowest. Therefore, the application of fertilizer solution concentration should be appropriately reduced. In this study, the ammonia nitrogen conversion rate was the highest with the concentration of fertilizer solution at 33.3 g/L. Due to the experimental setting of the dripper flow rate of 7 L/h, during the infiltration process, the casing has been fully stored, the water head in the emitter has been higher than the outlet hole, and some excess water is not able to infiltrate into the soil. According to the test results, it is recommended that when the dripper flow rate is less than 7 L/h, the water volume may completely penetrate, the fit of the emitter to the casing will be better, and excessive water will not flow out from the pores, which can better play the advantages of bubbled-root irrigation for efficient irrigation.

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Declarations

Conflict of interest The authors declare that they have no competing interests.

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