Influences of alternate partial root-zone irrigation and urea rate on water- and nitrogen-use efficiencies in tomato

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Abstract: Traditional water and fertilizer inputs are often much higher than the actual demands of tomato, which causes a reduction in water- and fertilizer-use efficiencies. To investigate the advantage of alternate partial root-zone irrigation (AI) on water- and nitrogen (N)-use efficiencies of tomato modified by water and N management, taking conventional irrigation (CI) as the control, the effects of AI on root morphology and activity, fruit yield and water and N use efficiency were studied using pot experiments. There were four combinations of irrigation levels and growing stages of tomato for AI, i.e. AI_1 (high water (W_H) from blooming to harvest stage (BHS)), AI_2 (W_H from blooming to fruit setting stage (BFS) and low water (W_L) at the harvest stage (HS)), AI_3 (W_L at BFS and W_H at HS) and AI_4 (W_L at BHS) at three urea rates, i.e. low urea rate (N_L), middle urea rate (N_M) and high urea rate (N_H) in the form of urea. Irrigation quotas for W_H and W_L in AI at BFS or HS were 80% and 60% of that in CI, respectively. Compared to CI, AI decreased water consumption by 16.0%-33.1% and increased water use efficiency of yield (WUE_y) and dry mass (WUE_d) by 6.7%-11.9% and 10.2%-15.9%, respectively. AI_1 did not decline yield, total N uptake (TNU) and N use efficiency (NUE) significantly. Compared to N_L, N_M enhanced tomato yield, TNU, WUE_y and WUE_d by 28.5%, 35.3%, 22.6% and 16.3%, respectively. Compared to CIN_L, AI_1N_M reduced water consumption by 12.5%, but increased tomato yield, TNU, WUE_y and WUE_d by 35.5%, 58.4%, 54.4% and 53.7%, respectively. Therefore, AI_1 can improve water use efficiency and total N uptake of tomato simultaneously at medium urea rate.

Keywords: alternate partial root-zone irrigation, nitrogen level, nitrogen uptake, tomato, water use efficiency, yield
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1 Introduction

As one of the common vegetables, tomato has the largest planting area all around the world[1]. Traditional water and fertilizer inputs are much higher than tomato demands, which reduce water- and fertilizer-use efficiencies[2,3]. Therefore, the optimization in water and fertilizer management of tomato is critical for high water- and fertilizer-use efficiencies.

Alternate partial root-zone irrigation (AI) is a water-saving irrigation technique aiming to alleviate water scarcity and enhance water use efficiency (WUE) in agriculture[4,5]. By changing wetting methods in the root-zone, AI sends water stress signal from roots to stomata, which not only decreases luxury transpiration, but also maintains relatively higher levels of photosynthesis rates and improves root absorption simultaneously[4]. Therefore, AI improves water- and

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fertilizer-use efficiencies[4,6]. Compared with conventional irrigation (CI), AI guarantees tomato fruit number, mean fruit weight, fruit dry mass[7] and yield[8], but it decreases water consumption, thereby increasing irrigation WUE[7-10]. AI promotes root hair growth, root activity and root development evenly in different root-zones; however, continuously wet or dry condition is not beneficial for the growth and development of root hairs[10-12]. In addition, AI promotes fertilizer availability, uptake and use efficiency, and decreases the risk of soil nitrate leaching when compared with CI[13].

Proper N supply strengthens root development, and improves tomato yield, dry mass accumulation and N uptake. But excessive N supply restricts the root development, delays growth and decreases tomato yield[14]. Tomato yield, dry mass and shoot N uptake rises greatly[14], but N uptake efficiency declines remarkably with the augment of N supply[15].

The previous study that alternate partial root-zone irrigation (AI) enhances water and nitrogen (N) use efficiency and yield, has not been done clearly and it still needs further investigation under different water and fertilization management conditions. Therefore, this study proposed that the alternate partial root-zone irrigation improved fruit yield and water- and nitrogen-use efficiencies of tomato under proper water and nitrogen management conditions, and its objective was to obtain the optimal mode of water and fertilizer supply of tomato plants.

2 Materials and methods

2.1 Experimental site and materials

The experiments were conducted from June to October in 2013 in a ridge-type greenhouse at Northwest A&F University in Yangling, Shaanxi, China (latitude 34°18′N, longitude 108°24′E, 521 m above sea level). The study site is located in a semi-arid zone, with a mean annual temperature of 12.5℃, a mean annual precipitation of 632 mm, a mean annual evaporation from a free water surface of 1500 mm, an average annual sunshine duration of 1900 h, and an annual accumulated temperature (higher than 10℃) of 3800℃. The greenhouse has a length of 36 m, width of 10.3 m and height of 4 m. During the experimental period, mean daytime and nighttime temperatures were 27℃-15℃ and the photon flux density ranged from 450 μmol/(m^2·s) to 800 μmol/(m^2·s) in the greenhouse. The experimental soil was alluvial soil (Fluvisols) and had a field capacity (FC) of 24% (mass by mass), organic matter content of 6.2 g/kg, available N content (1 mol/L NaOH hydrolysis) of 50.5 mg/kg, available P content (0.5 mol/L $NaHCO_3$) of 14.7 mg/kg and available K content (1 mol/L neutral NH_4OAc) of 140.5 mg/kg. The tomato species of *Solanum lycopersicum*, var. Maofen-802 was chosen as the experimental crop.

2.2 Experimental method

Five irrigation methods and three nitrogen (N) levels were carried out in the pot RCBD experiments. This experimental design yielded a total of 15 treatments and each treatment had six replicates. The five irrigation treatments used in this study were shown in Table 1. Irrigation methods included conventional irrigation (CI, both sides of the pot irrigated simultaneously at each watering) and four AI methods (AI, alternate watering on both sides of the pot) under different irrigation levels at various growing stages of tomato. Irrigation in CI was controlled by weighing the pots with electronic balance every day or every other day, and the soil water content was maintained from 70% to 85% FC. Irrigation quota for high water (W_H) and low water (W_L) in AI from blooming to fruit setting stage (BFS) or harvest stage (HS) judged by morphological characters was 80% and 60% of that in CI, respectively. Three urea rates included low urea rate (N_L, N 0.15 g/kg soil), medium urea rate (N_M, N 0.30 g/kg soil) and high urea rate (N_H, N 0.45 g/kg soil) in form of urea. All fertilizers were used with analytical reagents. Equal N solution was applied at 36 DAT (days after transplanting), 77 DAT and 94 DAT. P and K were applied in the powdered form of KH_2PO_4 mixed into the soil at the commencement of the experiments, and all treatments were supplied with 0.15 g K_2O/kg soil and 0.12 g P_2O_5/kg soil. As the soil water content was generally lower than the field capacity, water leakage from the bottom of the pots was negligible.

Pot experiments were conducted in plastic buckets (32.5 cm in diameter at the top edge, 28.5 cm in diameter at the bottom and 33 cm in depth). Nine holes were uniformly punched, and 2 cm thick sand was paved at the bottom of bucket to provide better aeration. The inside of all pots was evenly separated into two containers with plastic sheets sealed in the middle, and the water exchange among the containers was prevented. U-shaped notches were made in the center of plastic sheets for planting tomato. To prevent surface soil hardening from the irrigation, a PVC tube (2 cm in diameter) with holes (staggered three rows, 4 mm in diameter and 2.5 cm spacing) was installed in each bucket to supply irrigation water.

Table 1 Irrigation treatments for pot experiments

Irrigation method	Irrigation level and stage	
	Blooming to fruit setting stage /July 7 to 28	Fruit setting to harvest stage /July 29 to October 11
CI	70 to 85% FC	70 to 85% FC
AI_1	high water (W_H)	high water (W_H)
AI_2	high water (W_H)	Low water(W_L)
AI_3	Low water(W_L)	high water (W_H)
AI_4	Low water(W_L)	Low water(W_L)

Note: CI and AI represent conventional irrigation and alternate partial root-zone irrigation, respectively. Irrigation quota for high and low water in AI from blooming to fruit setting and harvest stage was 80% and 60% of that in CI, respectively.

Each bucket was filled with 21 kg air-dried soils after 2 mm sieving with a mean bulk density of 1.25 g/cm^3. Tomato seedlings were transplanted to each pot on the 21 DAT. Soil water regimes in all pots were maintained at the field capacity before the soil water was controlled. For AI treatments, at 10 d after transplanting, irrigation level was controlled at the two growth stages according to Table 1. Tap water (pH 7.2) was used as the irrigation water.

2.3 Plant samplings and measurements

Tomato fruits were harvested when approximately 80% of the fruits became red or orange. The root morphology, root activity, dry mass accumulation and N content of plant tissues were measured at the end of the experiments.

Root morphologies (root length, root area, root volume and root tip number) were measured using WinRHIZO analysis system (Reagent Instruments Inc., Quebec, Canada)[16]. Root activity was measured by the triphenyl tetrazolium chloride (TTC) reduction method and expressed as TTC reduction per root tip fresh weight in unit time (reduction intensity)[17].

At the harvest stage, plant samples were divided into stems, leaves, roots and fruits, which were firstly dried at 105℃ for 30 min, and further dried at 80℃ to a constant dry mass. After grinding and sieving, plant samples were digested with concentrated H_2SO_4 mixed with K_2SO_4-$CuSO_4$ catalyzer. Subsequently, the digested solution was used to determine N content using the Kjehldahl method (FOSS, KJELTEC 2300, Sweden)[18].

Total water consumption was calculated using the water balance equation. Water use efficiency on the basis of yield (WUE_y) or dry mass (WUE_d) was defined as the amount of yield and dry mass per unit water use, respectively. Root-shoot ratio was defined as the amount of root dry mass per unit shoot dry mass. N uptake was the product of N content and dry mass in different plant tissues, and total N uptake (TNU) was the sum of N uptake in different plant tissues. N dry mass production efficiency (NDMPE) was defined as the amount of total dry mass per unit TNU[19] and N uptake efficiency (NUE) was defined as the amount of TNU per unit N fertilizer used[20].

2.4 Statistical analysis

Analysis of variance (ANOVA) was performed using the two-way ANOVA from SAS software. All the treatment means were compared for marked differences among the treatments using the Duncan's multiple range tests at the significant level of $p_{0.05}$ using the SAS 8.2 for Windows software package (SAS Institute, USA).

3 Results

3.1 Root morphology and activity

There were significant effects of irrigation method, urea rate and their interaction on root length, root area, root volume, root tip number and root activity. As shown in Table 2, compared to CI, AI_1 raised root length, root area, root tip number and root activity by 23.9%, 19.5%, 18.6% and 14.6%, respectively, but it did not enhance root volume observably. AI_2 increased root area and root tip by 6.3% and 6.0%, but it did not enhance root length and diminish root volume and root activity prominently. AI_3 raised root length, root area, root tip number and root activity by 8.6%, 10.5%, 10.3% and 17.7%, respectively, but it did not reduce root volume remarkably. AI_4 declined root length, root volume, root tip number and root activity by 28.7%, 15.1%, 18.5% and 12.9%, but it did not decrease root area significantly. Compared to low urea rate (N_L), medium urea rate (N_M) augmented root length, root area and root tip number by 13.3%, 20.7% and 13.2%, but did not enhance root volume and root activity obviously. High urea rate (N_H) reduced root length, root volume, root tip number and root activity by 14.2%, 16.5%, 8.8% and 16.8%, and did not decrease root area greatly, indicating that N_M was beneficial for root growth of tomato plants. Compared to CIN_L treatment, AI_1N_M treatment increased root length, root area, root volume, root tip number and root activity by 39.2%, 52.7%, 20.9%, 52.2% and 38.0%, respectively.

Table 2 Effects of irrigation method and urea rate on root traits of tomato

Urea rate	Irrigation method	Root length /m plant^{-1}	Root area /cm^2 plant^{-1}	Root volume /cm^3 plant^{-1}	Root tip number	Root activity /mg (g·h)$^{-1}$
N_L	CI	39.99±0.92f	482.7±11.1f	6.42±0.08cd	4073±49def	173.13±9.64e
	AI_1	50.45±1.44b	580.9±34.9abc	7.33±0.38ab	5466±47ab	214.95±25.47abc
	AI_2	42.00±2.57e	527.1±17.1def	6.76±0.15bc	4681±206bcd	206.04±15.99bcd
	AI_3	43.36±2.42d	501.8±33.7ef	6.83±0.68bc	4634±94cd	221.90±5.34ab
	AI_4	25.85±1.23i	472.6±20.3f	6.30±0.17cde	3724±75ef	181.62±13.77de
N_M	CI	41.87±1.07e	577.6±22.1cde	6.82±0.25bc	4456±245de	188.61±19.22cde
	AI_1	55.69±2.22a	737.2±30.2a	7.76±0.17a	6198±135a	238.89±12.82a
	AI_2	48.58±1.51c	620.0±18.4bc	7.51±0.03ab	5434±250abc	196.33±14.06bcde
	AI_3	49.87±1.15bc	653.1±22.4b	7.48±0.34ab	5682±55a	236.69±3.76a
	AI_4	32.52±1.75h	507.3±27.3def	6.38±0.69cd	3786±136ef	174.73±13.83e
N_H	CI	37.14±0.94g	475.8±35.7f	6.76±0.36bc	4780±81bcd	194.14±7.76bcde
	AI_1	41.36±1.65e	517.6±31.0def	5.90±0.02def	4120±458def	183.19±5.72de
	AI_2	32.02±1.49h	485.7±23.4f	5.59±0.54ef	3988±36def	129.08±10.32f
	AI_3	36.04±0.28g	541.8±12.1def	5.54±0.64f	4360±247de	195.77±24.54bcde
	AI_4	26.46±0.27i	468.7±15.0f	4.31±0.38g	3338±87f	127.58±19.43f
Significance test (p values)						
Urea rate		<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Irrigation		<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Urea rate × irrigation		<0.0001	0.0380	0.0056	0.0110	0.0033

Note: Values are means ± standard errors (n=6). Different letters in the same column indicate significant difference at p<0.05. Symbols in the following tables and figures are the same as this table.

3.2 Yield and dry mass accumulation

Irrigation method and urea rate had marked effect on tomato yield. Compared to CI, AI_2, AI_3 and AI_4 reduced tomato yield by 21.3%, 13.3% and 28.2%, respectively, but AI_1 did not decrease yield observably (Table 3). N_M increased tomato yield by 28.5% but N_H did not enhance tomato yield observably when compared to N_L. And AI_1N_M treatment had the highest yield which was increased by 35.3% when compared to CIN_L treatment.

There were significant effects of irrigation method and urea rate and their interaction on shoot, root and total dry masses. Compared to CI, AI_1 enhanced root dry mass by 37.5%, but did not diminish shoot and total dry masses greatly (Table 3). AI_2 reduced shoot and total dry masses by 18.4% and 17.1%, but increased root dry mass by 10.0%. AI_3 declined shoot and total dry masses by 12.7% and 11.2%, but augmented root dry mass by 21.4%. AI_4 reduced shoot and total dry masses by 24.4% and 23.5%, but did not diminish root dry mass obviously. Compared to N_L, N_M increased shoot, root and total dry masses by 21.7%, 30.4% and 22.2%, but N_H decreased shoot, root and total dry masses by 8.7%, 10.2% and 8.8%. AI_1N_M treatment enhanced shoots, roots and total dry masses by 30.6%, 122.1% and 34.5%, respectively when compared to CIN_L treatment.

Notable effects of irrigation method and urea rate and their interaction on root-shoot ratio were found. Compared to CI, AI_1, AI_2, AI_3 and AI_4 increased root-shoot ratio by 48.8%, 33.7%, 38.3% and 25.3% (Table 3), showing that AI can promote the development of root system. N_M raised root-shoot ratio by 7.1% but N_H did not enhance root-shoot ratio when compared to

N_L. Compared to CIN_L treatment, CIN_M treatment did not augment root-shoot ratio remarkably, but other treatments raised root-shoot ratio by 17.7%-70.1%. Moreover, root-shoot ratio of AI_1N_M treatment was the highest, which was 1.70 times larger than that of CIN_L treatment.

Table 3 Effects of irrigation method and urea rate on yield and dry mass accumulation of tomato

Urea rate	Irrigation method	Yield/g plant^{-1}	Shoot dry mass/g plant^{-1}	Root dry mass/g plant^{-1}	Total dry mass/g plant^{-1}	Root-shoot ratio/%
N_L	CI	618.3±32.1def	57.96±5.45bc	2.60±0.04fg	60.56±2.10cd	4.49±0.08g
	AI_1	649.3±15.4cde	57.12±0.47bc	4.10±0.12cd	61.22±4.00cd	7.18±0.05ab
	AI_2	534.6±37.3efgh	54.80±5.91c	3.50±0.30de	58.30±5.80d	6.38±0.27cd
	AI_3	559.2±49.4efgh	55.77±7.85bc	3.59±0.11de	59.36±8.35d	6.44±0.28cd
	AI_4	509.3±35.4fgh	52.57±3.98cd	2.96±0.18efg	55.53±3.43de	5.63±0.13ef
N_M	CI	819.2±28.5ab	73.60±0.75a	3.32±0.06e	76.92±4.43ab	4.51±0.04g
	AI_1	837.6±34.2a	75.70±4.76a	5.78±0.04a	81.48±6.90a	7.63±0.08a
	AI_2	690.4±36.1cd	65.73±5.80ab	4.47±0.19bc	70.20±6.93bc	6.80±0.17bc
	AI_3	757.7±46.9abc	68.27±7.63a	4.82±0.07b	73.09±8.89ab	7.07±0.30b
	AI_4	583.4±27.1defg	55.23±2.38c	3.46±0.11de	58.69±4.81d	6.27±0.02d
N_H	CI	702.4±11.9bcd	68.18±1.05a	3.60±0.13de	71.78±6.36ab	5.28±0.41f
	AI_1	544.3±39.1efgh	49.89±3.44cd	3.21±0.05ef	53.10±3.97de	6.44±0.17cd
	AI_2	459.6±42.0gh	42.42±3.68d	2.51±0.09g	44.92±6.13e	5.91±0.31de
	AI_3	538.2±21.4efgh	50.29±1.88cd	3.14±0.03efg	53.42±1.56de	6.24±0.12d
	AI_4	443.3±29.9h	43.23±3.63d	2.59±0.30fg	45.82±1.56e	5.98±0.38de
Significance test (p values)						
Urea rate		0.0001	<0.0001	<0.0001	0.0002	<0.0001
Irrigation		<0.0001	<0.0001	<0.0001	<0.0001	0.0054
Urea rate×irrigation		0.0566	0.0148	0.0005	0.0115	0.0345

3.3 Water use efficiency

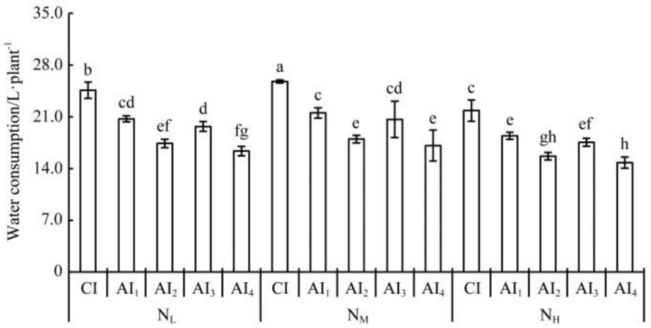
Irrigation method and urea rate had significant effects on water consumption. Figure 1a shows that compared to CI, AI_1, AI_2, AI_3 and AI_4 lowered water consumption by 16.0%, 29.3%, 19.8% and 33.1%, respectively. N_H decreased water consumption by 10.6% but N_M did not influence it significantly when compared to N_L.

There were marked effects of irrigation method and urea rate and their interaction on WUE_y. Compared to CI, AI_1, AI_2, AI_3 and AI_4 increased WUE_y by 11.9%, 10.3%, 7.4% and 6.7%, respectively (Figure 1b), suggesting that AI can greatly reduce water consumption and increase WUE_y simultaneously. N_M and N_H raised WUE_y by 26.2% and 27.8% at CI and N_M enhanced WUE_y by 21.9% at AI if compared to N_L. Compared to CIN_L treatment, other treatments increased WUE_y by 12.5%-54.5%. In addition, WUE_y at AI_1N_M treatment was the highest, which was 1.54 times higher than that of the CIN_L treatment.

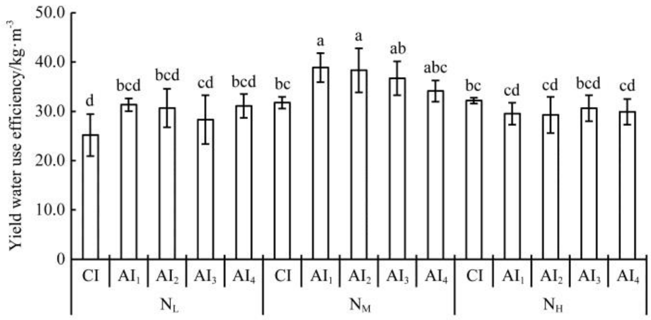
There were obvious effects of irrigation method and urea rate and their interaction on WUE_d. Compared to CI, AI_1, AI_2, AI_3 and AI_4 enhanced WUE_d by 10.2%, 15.9%, 9.9% and 13.6%, respectively (Figure 1c). N_M increased WUE_d by 16.3%, but N_H did not affect WUE_d greatly if compared to N_L. Compared to CIN_L treatment, other treatments improved WUE_d by 16.4%-58.5%. Moreover, AI_2N_M and AI_1N_M increased WUE_d by 58.5% and 53.7%, respectively.

3.4 Nitrogen use efficiency

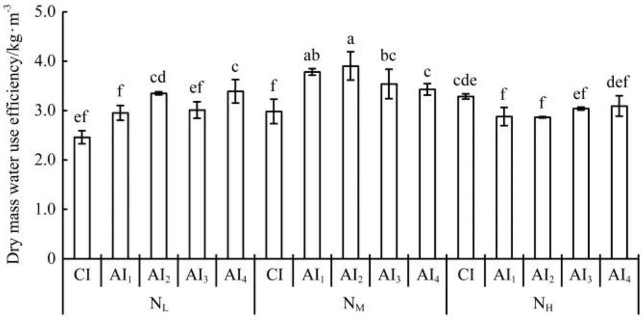
There were pronounced effects of irrigation method and urea rate and their interaction on total N uptake (TNU) and N use efficiency (NUE), and irrigation method and urea rate on N dry matter production efficiency (NDMPE) of tomato plants. Compared to CI, AI_1 did not affect TNU, NDMPE and NUE remarkably (Table 4). AI_2 decreased TNU and NDMPE by 10.4% and 8.9%, but did not affect NUE markedly. AI_3 reduced TNU and NUE by 10.6% and 6.9%, but did not affect NDMPE significantly. AI_4 declined TNU and NUE by 19.7% and 13.9%, but did not affect NDMPE greatly. Compared to N_L, N_M and N_H increased TNU by 41.4% and 46.2% at CI. At AI, N_M raised TNU by 33.7% but lowered NDMPE and NUE by 9.8% and 32.4%, and N_H reduced them by 18.0% and 63.1%, respectively. When compared to CIN_L treatment, AI_2N_H, AI_3N_L, AI_4N_H and AI_4N_L treatments did not affect TNU observably, but other treatments promoted TNU by 7.8%-58.4%, among then AI_1N_M reached the maximum. AI_3N_L and AI_4N_L treatments did not influence NUE greatly, but other treatments decreased NUE by 20.8%-67.6%.



a. Urea rate $p<0.001$, Irrigation $p<0.001$, urea rate × irrigation $p<0.001$



b. Urea rate $p<0.001$, Irrigation $p<0.001$, urea rate × irrigation $p=0.6389$



c. Urea rate $p<0.001$, Irrigation $p=0.0479$, urea rate × irrigation $p=0.0299$

Figure 1 Effects of irrigation method and urea rate on water consumption and water use efficiency of tomato

Table 4 Effects of irrigation method and urea rate on nitrogen use of tomato

Urea rate	Irrigation method	Total N uptake /g plant^{-1}	N dry mass production efficiency/kg kg^{-1}	N uptake efficiency/%
N_L	CI	1.27±0.06c	47.69±1.06a	42.33±1.36b
	AI_1	1.32±0.01c	46.50±3.04a	43.89±0.21ab
	AI_2	1.37±0.06c	42.59±1.39abc	45.62±1.44a
	AI_3	1.27±0.13c	46.92±1.30a	42.18±0.82b
	AI_4	1.26±0.09c	44.12±3.77ab	41.95±0.47b
N_M	CI	1.80±0.09ab	42.82±1.12abc	29.94±1.29d
	AI_1	2.01±0.11a	40.50±2.67bcd	33.52±1.26c
	AI_2	1.78±0.03b	39.41±2.47bcd	29.68±2.47d
	AI_3	1.71±0.03b	42.66±3.10abc	28.55±1.15d
	AI_4	1.46±0.05c	40.17±4.12bcd	24.35±0.13e
N_H	CI	1.86±0.04ab	38.67±0.34cd	20.62±1.07f
	AI_1	1.40±0.03c	37.87±1.13cd	15.58±0.92g
	AI_2	1.26±0.14c	35.68±1.47d	13.99±1.36g
	AI_3	1.42±0.03c	37.59±1.02cd	15.79±2.10g
	AI_4	1.23±0.07c	37.11±1.57d	13.72±1.26g
Significance test (p values)				
Urea rate		0.0002	0.0442	0.0001
Irrigation		<0.0001	<0.0001	<0.0001
Urea rate × irrigation		0.0019	0.9754	0.0011

3.5 Relationship among root morphology and activity and water and nitrogen use efficiency

Results show that there were marked linear correlations between tomato WUE_y and root area (WUE_y=0.0385 root area + 10.916, R^2=0.6359, p=0.0004), root volume (WUE_y=2.4064 root volume + 16.183, R^2=0.3409, p=0.0222) and root-tip number (WUE_y=0.0032 root-tip number + 17.369, R^2=0.4674, p=0.0050), but no remarkable linear correlations between tomato WUE_y and root length and root activity. There were obvious linear correlations between TNU and root length (TNU=0.0173 root length + 0.8001, R^2=0.3323, p=0.0245), root area (TNU=0.0024 root area+0.178, R^2=0.5129, p=0.0027), root volume (TNU=0.1787 root volume + 0.3302, R^2=0.3838, p=0.0138), root tip number (TNU=0.0002 root tip number + 0.4784, R^2=0.4691, p=0.0048) and root activity (TNU=4.1697 root activity + 0.6986, R^2=0.267, p=0.0487), respectively.

4 Discussion

4.1 Root morphology and activity

Root morphology and activity affect the absorption of water and nutrients[21,22]. In this study, compared to CI, AI_1 and AI_3 promoted root growth and enhanced root activity, which agreed well with the former result[23]. This is because alternate drying and wetting in soil environment can promote root compensation growth and metabolic capacity, which enhances root absorption capacity[12]. However, AI_2 and AI_4 reduced root activity and AI_4 inhibited the root growth significantly, because both AI_2 and AI_4 had low water supply over longer time periods (from fruit setting to harvest stage) and lower soil water content, which was not beneficial for root compensation function after re-watering. Thus only when soil water content was controlled at a relatively higher level (irrigation quota was 80% of that in CI), AI enhanced root growth. In this study, the roots in N_L and N_M grew vigorously, but N_H diminished root length, root volume, root tip number and root activity. This is due to the fact that higher solution concentration in soils caused by N_H was not beneficial for root growth and water and nutrient absorption. Previous results also showed that proper N supply promotes the root growth, but excessive N supply inhibits root development[24].

4.2 Yield and dry mass accumulation

In this study, AI_1 did not reduce tomato yield markedly, which agreed with the previous result[8]. But AI_2, AI_3 and AI_4 reduced tomato yield by 13.3%-28.2%, which might be associated with the degree of water stress, indicating that AI had the risk of reducing yield at low irrigation levels. The results also showed that tomato yield and total dry mass firstly enhanced and then decreased with the increasing of urea rate, which was in agreement with previous results[20,25]. This is due to the fact that severe water deficit inhibits crop root development, increases the viscosity of xylem sap, decreases crop absorption and transport of nutrient from soil, and inhibits chemical and dynamic availability of soil nutrient[26]. Moreover, AI promoted root-shoot ratio greatly when compared to CI, which might be attributed to AI regulating photosynthate distribution of root and shoot and optimizing root-shoot ratio[27,28].

4.3 Water use efficiency

Compared to CI, AI reduced water consumption but increased WUE_y and WUE_d significantly, which were in consistent with previous results[4,5]. WUE_y or WUE_d enhanced at CI with the augment in urea rate, but it initially increased and later decreased at AI, indicating that AI did not increase WUE significantly at higher urea rate. This was associated with lower soil water content in AI, mainly because that proper N rate promotes root growth and the ability of water absorption, decreases leaf water potential and improves leaf photosynthetic capacity. Additionally, it assimilates accumulation, plant development, plant water-lifting ability and soil water availability only under suitable soil moisture condition[29].

4.4 Nitrogen use efficiency

Compared to CI, AI_4 reduced total N uptake (TNU) and N use efficiency (NUE) significantly, because severe water deficit decreases root growth, root absorption area and capacity and increase the viscosity of sap flow in xylem. Thus the crop nutrient absorption and nutrient transport in soil are decreased. At the same time, water can affect chemical and dynamic availability of soil nutrients, so that available nutrients in the soil bulk cannot be changed into actual available nutrients in rhizosphere when severe water deficit occurs[26]. In this study, with the increase of urea rate, TNU enhanced at CI, but TNU was firstly augmented before a decrease at AI. The possible reason is that soil N concentration in N_H was too high at AI, which may diminish soil water potential, aggravate water stress and inhibit water and N absorption. But N_M promoted root growth and root distribution in soil, which is beneficial for water and N absorption in AI[30]. Our study found that N dry mass production efficiency (NDMPE) and N uptake efficiency (NUE) reduced with the increase of urea rate, indicating that there was diminishing return when fertilizer exceeded a certain amount. This is because high N supply promotes luxury N uptake, which lowers NDMPE and NUE[31]. Our study also show that AI_1N_M treatment promoted root growth, enhanced tomato yield, total dry mass, WUE_y, WUE_d and TNU simultaneously, displaying the synergistic effects of water and nitrogen. The interaction of physiological mechanism (root distribution and stomatal opening) and soil ecological incentives (soil N availability and soil microbial activity) improved WUE and N transformation and absorption at AI[32].

4.5 Relationship among root morphology and activity and water and nitrogen use efficiency

Root number and distribution are influenced by soil water and nutrient, but in turn, influences the distribution of soil moisture and nutrient, migration and consumption[33] and plant NUE and yield[34]. In this study, WUE_y and TNU respectively had linear relationships with root area, root volume and root tip number, which were in agreement with previous results[35]. Thus maintaining soil water environment and fertilizer by changing irrigation mode or water and fertilization supply strengthened root growth and development, thus plant absorption and utilization of soil water and fertilizer were improved.

5 Conclusions

(1) Compared to conventional irrigation (CI), alternate partial root-zone irrigation (AI) decreased water consumption but increased water use efficiency on the basis of yield (WUE_y) or dry mass (WUE_d). AI with high water from blooming to harvest stages (AI_1) did not lower yield, total N uptake (TNU) and N use efficiency (NUE) significantly.

(2) Compared to low urea rate (N_L), medium urea rate (N_M) greatly increased yield, total N uptake (TNU) and WUE_y and WUE_d. With the increase of urea rate, WUE and TNU enhanced at CI, but firstly rose and then declined at AI.

(3) WUE_y and TNU had linear relationships with root area, root volume and root tip number, respectively.

(4) Compared to CIN_L treatment, AI_1N_M treatment decreased water consumption, but enhanced tomato yield, TNU, WUE_y and WUE_d. Thus alternate partial root-zone irrigation with high water (80% of irrigation quota in CI) from blooming to harvest stages improved water use efficiency and total nitrogen uptake of tomato simultaneously at medium urea rate.

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