Effects of water and nitrogen coupling on the plant growth and quality of greenhouse tomatoes at the first flowering and fruiting stages

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Abstract: Good growth of tomato at the early growing stages is the key to final yield formation, for which water (W) and nitrogen (N) applications are two necessary factors. In this study, two irrigating systems (W1, W2) and three N applications (N1, N2, N3) were interacted (W×N) to plant the cherry tomato variety "Jinling Meiyu" in greenhouse. W1 (reduced irrigation) and W2 (normal irrigation) had a 7:9 irrigated ratio based on former research. N1, N2, and N3 were set at 100%, 80%, and 60% normal N application, respectively. The tomato plant height (PH), stem circumference (SC), number of leaves (NL), number of first order fruits (NF), the single fruit weight (SFW), contents of fruit Vitamin C (VC) and soluble sugar (SS), fresh weights of root (RW), leaf (LW), and plant stem (PSW), as well as leaf chlorophyll fluorescence value (SPAD), temperature (T), humidity (RH), and nitrogen content (N) were investigated at the first flowering and fruiting stage. The results showed that W×N had significant impacts on early plant growth and fruit quality of tomato. W2N2 obviously received the largest values of tomato PH (152.5 cm), SC (4.1 cm), NF (11 fruits/plant), and LW (45.0 g/plant), but obtained the lowest VC (9.71 mg/kg) and SS (2.40%). However, W1N3 had the largest values of leaf RH (56.9%), N contents (14.23 mg/g), and VC (16.29 mg/kg), with NF also at 11.0 fruits/plant. W2N1 significantly had the highest RW (14.4 g/plant), PSW (71.8 g/plant), and SFW (21.3 g/fruit). W2N3, W1N1, and W1N2 obtained the most NL (103.7 pieces/plant), SS (4.06%), and leaf SPAD (36.85), respectively. Pearson correlation analysis results showed PH negatively significantly correlated with NF (p<0.05). The leaf SPAD positively significantly correlated with PH (p<0.05) and RH (p<0.01), but negatively significantly correlated with SC (p<0.05) and T (p<0.01). Moreover, leaf N content also had a positive significant correlation with PH (p<0.05), and an extremely positive significant correlation with RH and SPAD (p<0.01). However, it negatively significantly correlated with SC (p<0.01) and T (p<0.05). Significantly, VC had positive correlations with PSW, leaf SPAD, and N content (p<0.05). SS negatively correlated with PSW (p<0.05) and T (p<0.01), and extremely significantly positively correlated with SPAD (p<0.01). Additionally, RW had an extremely significant relationship with PSW (p<0.01). Two-factor analysis of variances showed W extremely significantly influenced leaf T, RH, SPAD, and N content (p<0.001), as well as SC (p<0.01) and SS (p<0.05). Meanwhile, N management extremely significantly influenced LW (p<0.001), RW (p<0.01), and leaf T (p<0.05). However, W×N obviously significantly influenced just PSW (p<0.01), RW (p<0.001), and VC (p<0.05). Taking all factors into account, the early reasonable W×N management could promote growth of tomato plants and fruit quality at the first fruiting and ripening stage. These results could provide a foundation for the subsequent growth of tomato fruits and could also be beneficial for the precise management of greenhouse tomatoes at the early growing stages.

Keywords: greenhouse tomato, water and nitrogen interaction, leaf growth, SPAD value, nitrogen
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1 Introduction

Tomato (*Solanum lycopersicum* L.) is recognized as a global vegetable with positive health benefits[1]. In China, planting area and yield of greenhouse tomato ranked the first in facility agriculture, at 95.14×10^4 hm^2 and 48.75 million t, respectively, in 2020[2,3]. Water (W) and fertilization (F) management are the important factors affecting tomato growth, fruit formation, and nutrition.

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Unreasonable W and F management has been found to affect tomato growth and quality, cut into economic benefits, waste resources, and pollute groundwater, especially in greenhouse[4-8]. Good growth of tomatoes in the former stages is the key to final yield formation, and high tomato yields are associated with good plant dry matter accumulation and single plant fruit number[4,9]. The amount of irrigation or nitrogen (N) application has significant impacts on tomato plant height (PH), stem diameter (SD), chlorophyll content, and plant dry matter[10-12]. Specifically, tomato plants are most sensitive to water deficit during germination, seedling, and flowering periods, and decreasing soil water can inhibit its PH and SD growth[13-17]. An increasing appropriate irrigation amount can improve tomato PH, SD, chlorophyll content, biomass, and nutrients absorption at different stages[16,18,19]. Significantly, water stress inhibits the nutrient absorption of tomatoes during flowering and fruiting stage, especially with reduced tomato N absorption, PH, and biomass by high irrigation[20]. Although a certain degree of water deficiency can promote tomato plant growth[4,21], some severe water stress inhibits the growth of tomato aboveground parts[22]. Furthermore, some water-saving irrigation can promote tomato growth and fruit quality by affecting leaf photosynthate accumulation and distribution[23-25]. Significantly, a certain low irrigation can accelerate the flowering and fruit developmental stage and decrease fruit numbers[26]. Additionally, a reasonable irrigation deficit increases the soluble sugars (SS) and Vitamin C (VC) content[27,28]. Meanwhile, a reasonable fertilization can improve plant growth and fruit of facility tomatoes. N is reported to have significant impacts on tomato plant growth and development[29]. Han et al.[30] found that a reasonable N application can promote the growth of plants and the chlorophyll content in leaves, thereby improving the dry matter and N accumulation in the aboveground parts. Obviously, some decreased N fertilizer adds the relative value of leaf chlorophyll content (SPAD) at first, but increased N application to some extent improves tomato PH and SD[16,31]. Evidently, an adequate N fertilizer promotes tomato root morphological development and the aboveground dry matter accumulation during the seedling stage[32,33]. Particularly, chlorophyll contains a certain amount of N, which could affect photosynthesis and the formation of photosynthetic products in leaves[34]. One study believed SS and VC contents in tomato fruit not to be influenced by fertilization[35], but the former research found N fertilizers obviously significantly influenced VC and SS contents of cherry tomato[28]. Notably, the effect of water and fertilization interaction (W×F) has effects on tomato plant growth and development[4,36]. Reducing water and fertilization amounts to some extent at the same time would gradually decrease tomato PH and SD, delay flowering time, inhibit fruit growth, and finally reduce yield[15,37]. Also, some water-saving irrigation and a reasonable NPK ratio interaction increases the dry biomass and chlorophyll content of tomatoes[38,39]. Furthermore, the combined irrigation amount and N application (W×N) has been found to be beneficial for improving PH and SD; particularly, the N application and irrigation at seedling stage could significantly impact tomato SD[16]. Zhang et al.[40] also found that some different water-saving degree and N application interactions had significant impacts on tomato PH, SD, and chlorophyll content. Nowadays, facing the severe global shortage of soil and water resources, it is urgently necessary to study the comprehensive effects of water and N, especially on maximizing their coupling effects on tomato cultivation for sustainable agricultural development[16,41,42]. As excessive N fertilizer and soil water deficiency obviously harm tomato seedlings[43], some accurate water and fertilizer managements are necessary to maximize greenhouse tomato growth, yield, and quality[44]. The plant height, biomass, single fruit weight, and leaf growth are important indices affecting tomato fruit yield, especially in the early growing stages. Moreover, fruit VC and SS are also important indices for tomato quality, but the influence of W×N on these has still not been fully ascertained[28]. Therefore, in this paper, the highly effective water and fertilizer coupling technology used to develop facility agriculture[28,45] was selected to manage a cherry tomato plant growth in a pot experiment at the first flowering and fruiting stage. The tomato plant agronomic growth, fresh biomass, fruit number, single fruit weight, tomato fruit VC and SS, as well as leaf chlorophyll fluorescence value (SPAD), temperature, humidity, and N concentration, were investigated under six W×N treatments. This study's objectives were to: 1) investigate the effects of different W×N treatments on early growth of tomato root, stem, and leaf, as well as number, weight, and quality of the first order fruit; 2) analyze the main growth factors based on correlation analysis, and explore the effects of single W, N, and W×N on these factors; and 3) preliminarily obtain some W×N patterns beneficial for good growth of cherry tomato plant and first order fruits in greenhouse at the early growing stages.

2 Materials and methods

2.1 The tested soil

The tested soil was paddy soil collected from rice-wheat-vegetable rotation in Jiangsu Academy of Agricultural Sciences (32°03′N, 118°88′E). Its basic properties were: pH 8.6, organic matter 1.5%, available nitrogen 68.3 mg/kg, available phosphorus 27.2 mg/kg, available potassium 170.0 mg/kg, total nitrogen 0.10 g/kg, total phosphorus 0.8 g/kg, and total potassium 17.1 g/kg.

2.2 Experiment design

The pot experiment was carried out in the greenhouse of the College of Horticulture, Jinling Institute of Technology (32°12′N, 118°81′E). The used circular potting container was made of polyvinyl chloride, with 28 cm upper diameter, 24 cm bottom diameter, and 26.5 cm depth. Each pot contained 5 kg soil. All experimental pots were put in a plastic shed of 1.5 m width, 1.8 m height, and 2.5 m length, which was put in a big glass greenhouse. The layout of all treatments was firstly put in sequence during the seedling recovery period. After then the layout was randomly adjusted at least once in each growing stage. The actual adjustment dates were after measuring plant height (PH) and stem circumference (SC) on the 15th, 27th, 37th, 46th, 57th, and 86th day after transplanting. The changes of shed environmental indicators were observed by two precise environmental monitoring and controlling instruments (HT-2000 Carbon dioxide detector, Dongguan Wenxiang Technology Co., Ltd, China; Lvkedu, LKD-RMU series, model 597, China)[45]. These were to make appropriate layout adjustments based on environmental changes to ensure consistent environmental control. The planted cherry tomato “Jinling Meiyu” was obtained from Jiangsu Academy of Agricultural Sciences, as a limited growth type F1 hybrid bred from “jsct10” as the female parent and “jsct17” as the male parent[46]. It has the characteristics of strong growth, good flavor, resistance to storage and transportation, and strong disease resistance, and has both edible and ornamental value, with high cultivation efficiency[47]. The six W×N treatments were set as W1N1, W1N2, W1N3, W2N1, W2N2, and W2N3. W1 (reduced amount) and W2 (normal amount) were two irrigation systems at a ratio of 7:9. W1 and W2 displayed soil moisture content between about 60%-80% of the soil field capacity and 75%-100% of the soil field capacity[28], respectively. Mainly, a soil moisture tester (TR-6D, Beijing Shunkeda Technology Co., Ltd) was used for daily testing. If the soil moisture were below the lower limit of W1 and W2 ranges, irrigating would be done according to the above irrigation needs. The actual irrigation volumes of W1 and W2 were 700 mL and 900 mL per plant on the first, 10th, and 19th day after transplanting. Then they were 400 mL and 515 mL on the 26th and 73rd day after transplanting, 1000 mL and 1285 mL on the 41st day after transplanting, and 300 mL and 385 mL on the 63rd and 71st day after transplanting. The urea-nitrogen application rates were 100% (N1, 300 kg/hm^2), 80% (N2), and 60% (N3). All plants were applied with calcium superphosphate (P_2O_5) at 180 kg/hm^2 and potassium sulfate (K_2O) at 400 kg/hm^2. The fertilizing system was set with 30% N, 70% P, and 30% K as basic fertilizers and was applied on the 19th day after transplanting. It was 30% N and 30% P on the 41st day after transplanting, with 20% N and 30% K on the 52nd day after transplanting, and 20% N and 40% K on the 71st day after transplanting. The tomato seedlings (about 10 cm height) were transplanted on October 7, 2021. As the plants grew, two main branches and vines were kept with the remaining lateral buds removed on the 40th day after transplanting. Other planting management followed normal production planting management procedures. All plants were collected on the 96th day after transplanting.

2.3 Observed indices and methods

Plant height (PH) and stem circumference (SC) were obtained by a flexible ruler (accuracy of 0.1) on the 15th, 27th, 37th, 46th, 57th, 86th, and 96th day after seedling transplanting. The PH was measured from the distance from the roots to the top of the plant. The number of leaves (NL), number of first order fruits (NF), and single fruit weight (SFW), fresh weight of root (RW), leaves (LW), and aboveground stem (PSW) were recorded on the 96th day after transplanting. Chlorophyll fluorescence value (SPAD), temperature (T), humidity (RH), and nitrogen concentration (N) of leaves were observed by a chlorophyll fluorometer (CK-502S, China) on the 14th, 15th, 16th, 17th, 18th, 19th, 20th, 21st, 22nd, 23rd, 24th, 25th, 26th, 27th, and 96th day after seedling transplanting. The tested leaves were selected according to the steps outlined by Li et al.[48] The contents of quality indices Vitamin C (VC) and soluble sugar (SS) were tested by the anthrone colorimetry method and the molybdenum blue colorimetry method[28,49], respectively.

2.4 Data analysis

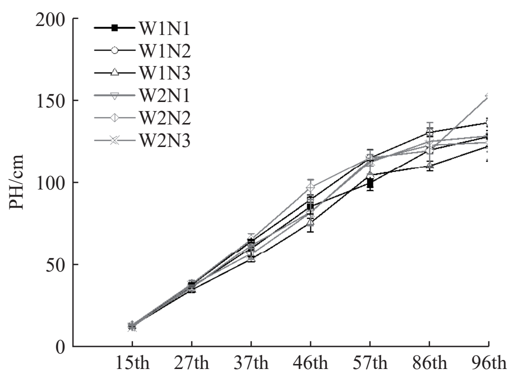
All data were first dealt with by Microsoft Excel 2016 (Microsoft Corp., Redmond, WA, USA), and figures were drawn by Origin 2024 (OriginLab Corporation, Northampton, Massachusetts, USA). The agronomic growth data were presented as the mean±SE of three replicates. Statistical differences (p<0.05) among individual treatments were measured using Duncan's multiple comparison tests (one-way ANOVA) in IBM SPSS Statistics v.27.0 (IBM Corp., Armonk, NY, USA). Pearson correlation analysis method was used to analyze the correlation between all different indicators. The influences of single irrigation (W), single nitrogen fertilization (N), and their interactions (W×N) were analyzed by two-way ANOVA analysis[28,45].

3 Results

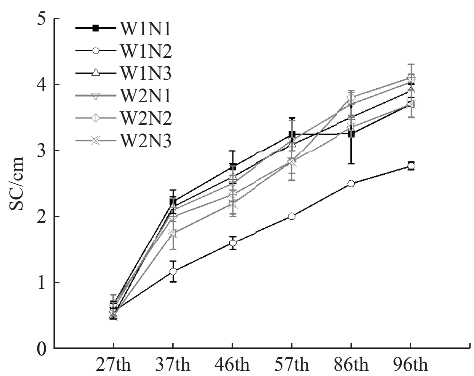
3.1 Agronomic growth indicators

3.1.1 Plant height and stem circumference

Figure 1a shows the dynamic changes of tomato plant height (PH) under all W×N treatments after transplanting. Their production rates were very fast before the 57th day after transplanting. Then, all slowed down improvement except W2N2, which saw a rapidly improved PH after 86 growth days. It had the highest value at 152.5 cm on the 96th day after transplanting, while W1N3 met with the lowest PH at 122.3 cm. Compared to PH on the 15th day after transplanting, both W2N2 and W1N2 had significant increment values. Figure 1b displays how the growth of stem circumference (SC) slowed down after the 37th growth day. Remarkably, W1N2 received the lowest values at all times after the 27th day. The treatment of W2N2 still had the largest SC at 4.1 cm on the 96th day after transplanting, while W1N2 had the smallest SC at 2.8 cm. All treatments under W2 and W1N3 had larger increments compared to the 27th growing day. Additionally, the increments under W1 significantly differed with each other. W2N1 received a growth trend at a relatively high and stable level at all times.



a. PH of tomato



b. SC of tomato

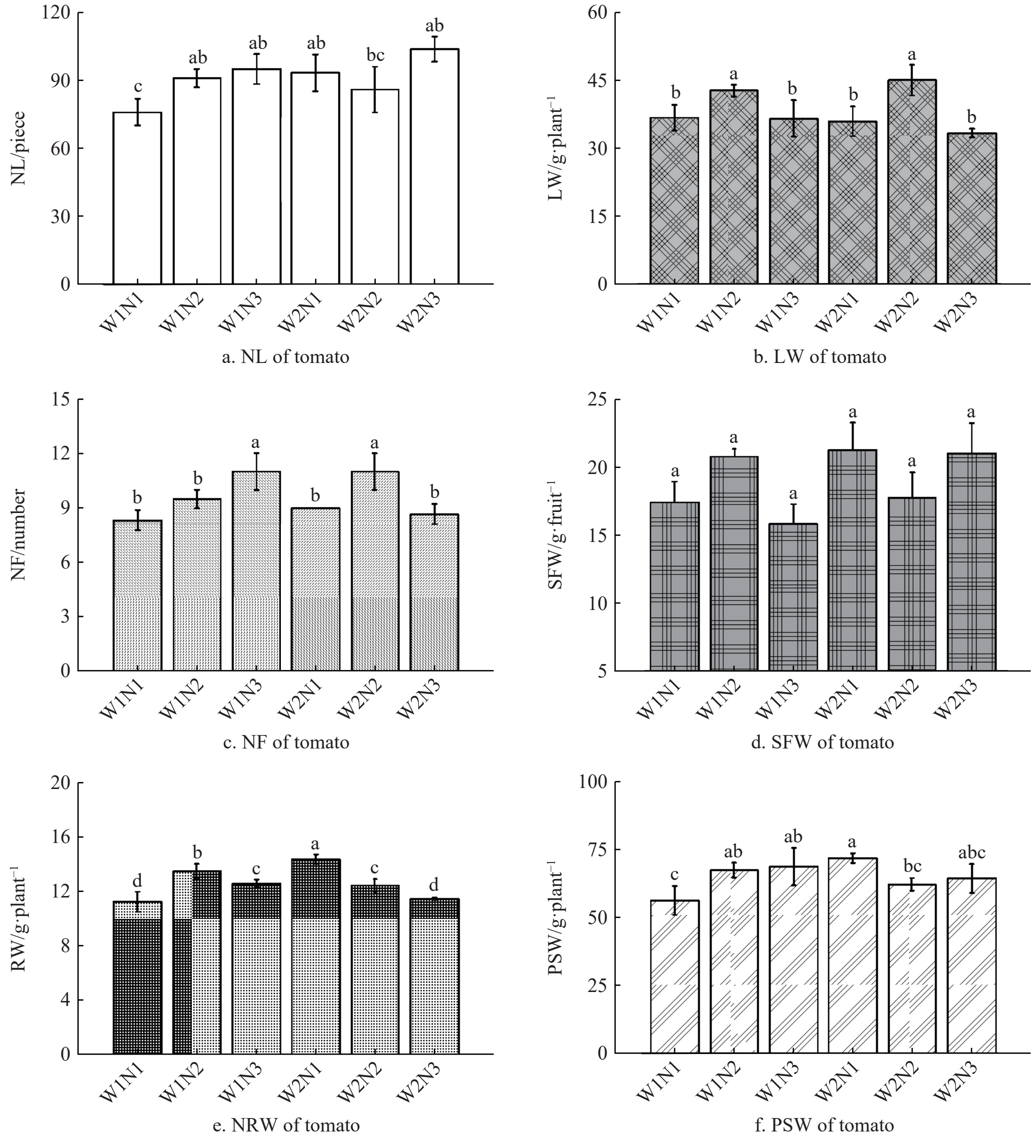
Note: W1N1: reduced irrigation amount and 100% urea-nitrogen application rate; W1N2: reduced amount and 80% urea-nitrogen application rate; W1N3: reduced amount and 60% urea-nitrogen application rate; W2N1: normal amount and 100% urea-nitrogen application rate; W2N2: normal amount and 80% urea-nitrogen application rate; W2N3: normal amount and 60% urea-nitrogen application rate; PH: Plant height; SC: Stem circumference. The error bar represents the standard error of each treatment (n=3). Same as the figures below.

Figure 1 Changes of tomato PH (a) under all W×N treatments on the 15th, 27th, 37th, 46th, 57th, 86th, and 96th day after transplantation, with SC (b) on 27th, 37th, 46th, 57th, 86th, and 96th day after transplantation

3.1.2 Plant fresh biomass

W2N3 obtained the most leaves (NL) at 103.7 pieces per plant

(Figure 2a) on the 96th day after transplanting, significantly surpassing W1N1 (76.0 pieces/plant) and W2N2 (86.0 pieces/plant). Furthermore, the results showed W2N2 and W1N2 both obviously met with the largest LW values at 45.0 g/plant and 42.7 g/plant (p<0.05, Figure 2b), with no significant differences between the remaining treatments (p>0.05). The number of first order fruit (NF) demonstrated that W1N3 and W2N2 both significantly received the maximum numbers of 11 first order fruits (p<0.05, Figure 2C), while W1N1 got the minimum at 8 fruits/plant. Obviously, the single fruit weight (SFW) demonstrated there was no significant difference between all W×N treatments (p>0.05, Figure 2d). Treatments of W2N1 (21.3 g/fruit), W2N3 (21.0 g/fruit), and W1N2 (20.8 g/fruit) all clearly received the highest SFW values (p<0.05). Additionally, W2N1 obtained the largest fresh weight of root (RW) at 14.4 g/plant, significantly differing with the rest of the treatments (p<0.05, Figure 2e). W2N3 and W1N1 both had by far the lowest RW values, at just 11.5 g and 11.3 g per plant (p<0.05). Obviously, W2N1 (71.8 g/plant) also had the highest PSW at 71.8 g/plant (p<0.05, Figure 2f), significantly differing with the lowest values of W1N1 (56.3 g/plant) and W2N2 (62.2 g/plant).



Note: The lowercase letters in the same column indicate that the difference between treatments was significant at p<0.05 with Duncan's multiple range test. NL: Number of leaves; LW: Leaf weight; NF: Number of fruits (F) before picking (the first fruits); SFW: Single fruit weight; RW: Root weight; PSW: Plant stem weight. The error bar represents the standard error of each treatment (n=3). Same as the figures below.

Figure 2 Conditions of NL (a), LW (b), NF (c), SFW (d), RW (e), and PSW (f) of tomato on the 96th day after transplantation under all W×N treatments

3.2 Leaf indices

3.2.1 SPAD value

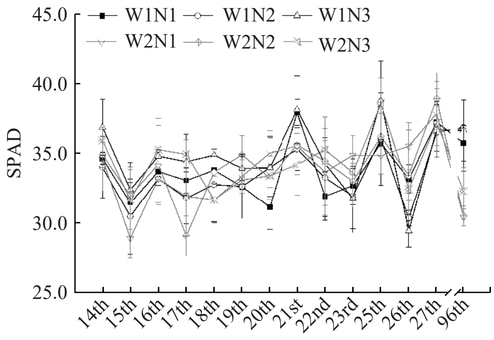
Figure 3 demonstrates that the values of SPAD under all treatments show a "W"-shaped fluctuation trend over time. On the beginning of the 14th day after transplanting, W1N3 got the highest SPAD at 36.87, while W1N2 had the lowest at 34.00. Significantly, SPAD under W1N3 stayed in a steady trend of higher values, but then underwent a large fluctuation. However, W2N2 reached a significant lowest value on the 17th day, passing over to be the largest on the 26th day. Significantly, it nearly went down to the bottom on the 96th day, when W1N2 reached the highest value at 36.85, and W2N1 had the smallest SPAD. Obviously, W2N1 and W2N3 both had a decreasing SPAD between the 16th and 19th day. Noticeably, treatments under W1 might enhance SPAD at the starting and later stages. In the middle few days, W2 treatments could improve the value.

3.2.2　Temperature (T) and humidity (RH)

The changes of leaf temperature (T) and humidity (RH) of tomatoes growing under all treatments are presented in Figure 4. Leaf T changes over time were consistent under all treatments (Figure 4a). The significant difference among all treatments popped on the 26th day after transplanting, when W1N1 got an extremely low T. However, all W2 treatments had higher T values until the 96th day. T value under W2N3 almost stayed at the top except on the 14th, 15th, 22nd, and 25th day. Meanwhile, T under W1N1 nearly stayed at the very bottom. The dynamic trend changes of RH (Figure 4b) under all W×N treatments were similar to the SPAD. All W×N treatments had up and down fluctuations, and significant interaction between water and fertilizer. Significantly, RH on the 96th day displayed higher values under W1 treatments.

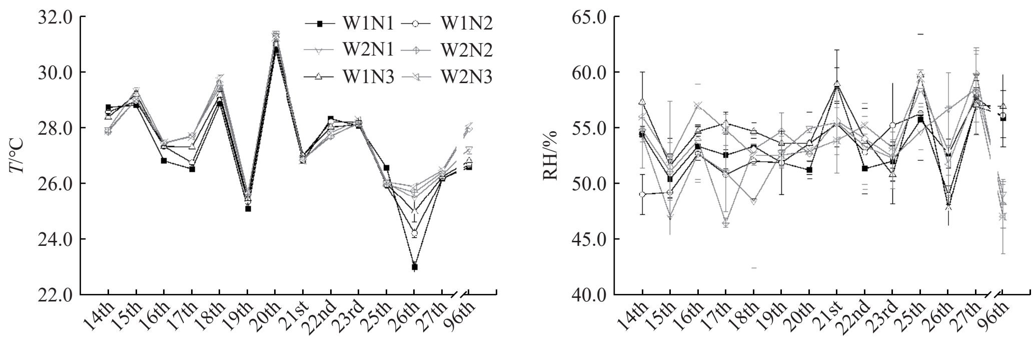
3.2.3　N content of leaf

Figure 5 demonstrates the changing trends of N contents under all W×N treatments after transplanting. The W-shaped fluctuation changes display that all N3 treatments got higher N before the 18th day after transplantation, then a decreased trend popped on W2N3 until the 21st day. Their N also went down on the 23rd and 26th day. W1N2 and W2N1 both kept with the lowest trends of N, but W2N1 received its highest N values on the 20th and 26th day, respectively. N under W1N2 increased to the top on the 23rd day. W1N1 and W2N2 always stayed at a mid-low N level. However, W1N1 and W2N2 reached their top N value on the 21st and 27th day, respectively. W2N2 on the 17th and 96th day, W1N1 on the 20th day, and W1N3 on the 26th day received the lowest N values, below 12.10 mg/g. W1N3 and W1N1 had evident high values at 14.37 mg/g and 14.70 mg/g (on the 21st day), with W1N3 and W2N3 obtaining evident high values at 14.93 mg/g and 14.87 mg/g (on the 25th day). W2N2 showed the highest N value among all values at 14.97 mg/g on the 27th day. As the tomato plant grew, the leaf N contents under all W×N treatments declined on the 96th growing day. The treatment of W1N3 achieved the highest N at 14.23 mg/g, while W2N2 met with the lowest at 12.02 mg/g.



Note: SPAD: Chlorophyll fluorescence value. Same as the figures below.

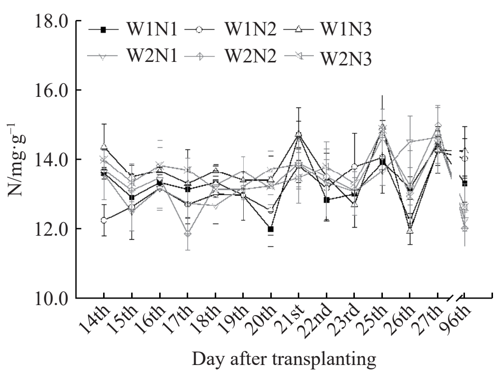
Figure 3　Changes of SPAD under all W×N treatments on the 14th, 15th, 16th, 17th, 18th, 19th, 20th, 21st, 22nd, 23rd, 25th, 26th, 27th, and 96th day after transplantation



a. *T* of tomato　　b. RH of tomato

Note: T: Leaf temperature; RH: Relative humidity of leaves. Same as the figures below.

Figure 4　Changes of T (a) and RH (b) under all W×N treatments on the 14th, 15th, 16th, 17th, 18th, 19th, 20th, 21st, 22nd, 23rd, 25th, 26th, 27th, and 96th day after transplantation



Note:N: Nitrogen content of leaf. Same as the figures below.

Figure 5　Changes of N under all W×N treatments on the 14th, 15th, 16th, 17th, 18th, 19th, 20th, 21st, 22nd, 23rd, 25th, 26th, 27th, and 96th day after transplantation

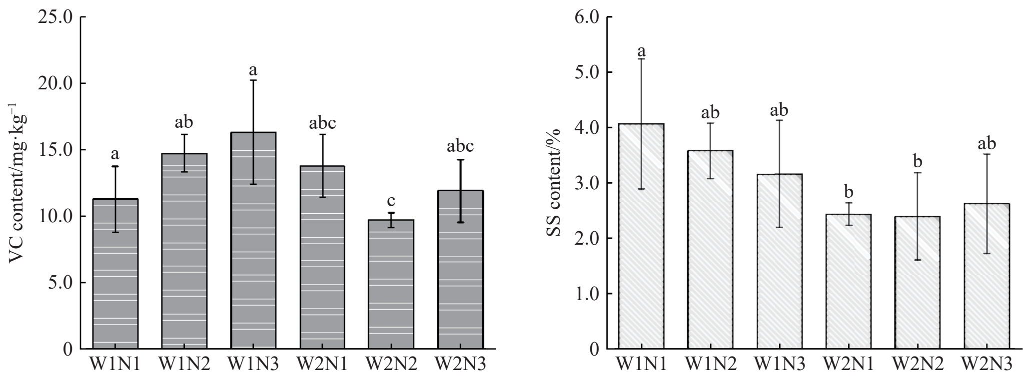
3.3　VC and SS contents of tomato fruit

Results from Figure 6a show that the decreased N applications could improve tomato VC content under the W1 irrigation system. However, reduced N application under W2 did not enhance VC. Among all treatments, W1N3 received the maximum VC value at 16.29 mg/kg, while W2N2 obtained the lowest VC content at 9.71 mg/kg. As for tomato SS content, there was an opposite pattern of change (Figure 6b). The reduced N application did not enhance the SS under W1, which could promote SS under W2. Therefore, W1N1 and W2N2 met with the largest and smallest content of SS at 4.06% and 2.40%, respectively. Due to some significant differences between repetitions under some treatments, multiple comparison results from Figure 6 will not be discussed or analyzed.

3.4　Pearson correlation analysis

All above indicators on the 96th day after transplanting were done by Pearson correlation analysis at significance levels of 0.05 and 0.01. The results of Figure 7 show that the N content had highly significant positive correlations (p<0.01) with RH (r=0.83) and

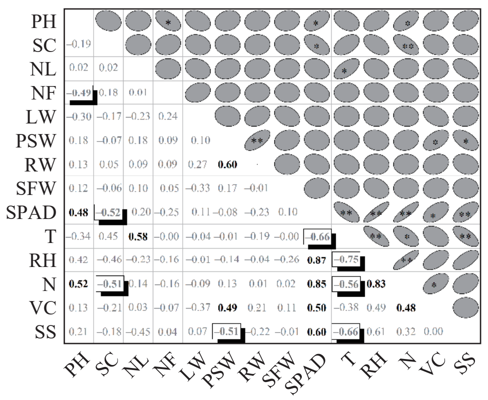
SPAD (r=0.85), and obviously positive correlations (p<0.05) with PH (r=0.52) and VC (r=0.48). However, N showed significant negative correlations with T (r= –0.56, p<0.05) and SC (r= –0.51, p<0.01). The leaf RH had extremely significant positive and negative correlations with SPAD (r=0.87, p<0.01) and T (r = –0.75, p<0.01), respectively. SPAD also presented an extremely significant negative correlation with T (r= –0.66, p<0.01), and obtained significant negative correlation with SC (r= –0.52, p<0.05). Furthermore, SPAD also had highly significant positive correlation with SS (r=0.60, p<0.01) and obvious positive correlation with VC (r=0.50, p<0.05). Moreover, PH evidently received a positive correlation with SPAD (r=0.48, p<0.05), while negatively correlating with NF at r= –0.49. Additionally, an extremely significant relationship presented between PSW and RW (r=0.60, p<0.01). SS also had an extremely significant negative correlation with T (r= –0.66, p<0.01), while significantly negatively correlating with PSW (r= –0.51, p<0.05).



a. VC of tomato b. SS of tomato

Note: VC: Vitamin C; SS: Soluble sugar. Same as the figures below.

Figure 6 VC (a) and SS (b) contents of tomato on the 96th day after transplantation under all W×N treatments



Note: * and ** display Pearson correlation analysis with significance levels at 0.05 and 0.01, respectively. The black number and oval border mean positive correlation. The gray number and oval border with shadow mean negative correlation.

Figure 7 Results of Pearson correlation analysis between all indicators (n=18)

4 Discussion

4.1 The coupling effect of W×N on the growth of tomato plants

In this article, the growth data of tomato at the first flowering and ripening stage differed between different irrigating systems and nitrogen managements. Moreover, the irrigation and fertilizing N could obviously have an effect on plant early growth indices (Figure 1 and 2). Some research studies had found that the growing indices of plant height (PH), stem diameter value (SD), and leaf number (NL) were the most intuitive indicators reflecting the growth trend of tomatoes, as well as the absorption and utilization of nutrients[50,51]. Additionally, the irrigation had been found to significantly impact tomato PH, SD, and NL[16]. Especially, the irrigation during the flowering and fruiting period obviously affected tomato PH, and during the seedling stage significantly impacted SC (10-40 days after transplanting was the main growth stage for tomato stem thickness)[16]. Dynamic changes of PH and SC (directly proportional to SD) in this paper demonstrated that a higher irrigation amount could enhance PH under N2 and N3, but decrease SC under N1 and N3 at about one month after transplanting. After then, the N2 treatment greatly promoted them under W2, with improved PH under W1. However, N2 decreased SC under W1. The above results show that increasing irrigation and fertilization to some extent could significantly improve tomato PH and SC, which was similar to an existing study[28]. However, the results of this study also show that reducing water and N fertilizer application to some extent could restrain PH and SC, which was similar to the studies [15] and [40]. Furthermore, it might be that the overuse of N and the soil irrigation deficit decreased the biomass of tomato seedlings[28]. The large irrigation amount or N leaching to lower soil layers could reduce available N in the upper soil layer, thereby inhibiting the shoot growth of tomatoes caused by insufficient nitrogen nutrition[52,53]. Furthermore, the two-factor interaction results show that irrigation had an extremely significant influence on SC on the 96th day (p<0.01, Table 1).

Table 1 Two-factor interaction results of all investigated indices on the 96th day after transplanting

Factors	PH	SC	NL	NF	SFW	LW	PSW	RW	SPAD	T	RH	N	VC	SS
W	ns	**	ns	ns	ns	ns	ns	ns	***	***	***	***	ns	*
N	ns	ns	ns	ns	ns	***	ns	**	ns	*	ns	ns	ns	ns
W×N	ns	ns	ns	ns	ns	ns	**	***	ns	ns	ns	ns	*	ns

Note: W, N, and W×N mean effects of irrigating, fertilizer, or watering-N fertilizer interaction by two-way ANOVA analysis, with ***, **, and * indicating extremely significant at 0.1%, 1%, and 5%, respectively. The ns means no significant difference.

It should be noted that adequate application of water and nitrogen (W1N1) did not increase leaf number and leaf biomass (Figure 2a). However, the reduction of water also could enhance NL, and the decreased N application (N3) improved the effect at the first flowering stage. It might be that the N level could alter stem and leaf structures to meet plant water and nutrient transport requirements[54], and the lower N application could adjust the stem to absorb nutrients to promote leaf growth. Noticeably, the N2 under W1 could enhance NL more than that under W2, which might show that reduced W treatment could benefit leaf number growth. Significantly, N2 promoted the improvement of LW under any irrigation system (Figure 2b), which indirectly reduced NL. Moreover, two-factor interaction results demonstrated that N application had an extremely significant influence on LW (p<0.001, Table 1). The effect of irrigation during the flowering and fruiting period on tomato PH reached a significant level, while the W×N effects during the seedling stage on tomato SC reached a significant level[16]. As for fresh biomass, N1 obviously reduced RW and PSW under W1, but significantly increased them under W2 (Figure 2e and 2f). Two-factor interaction results demonstrated that N application had an extremely significant influence on RW (p<0.01, Table 1). It might be that N was closely related to the synthesis of photosynthetic pigments, the improvement of photosynthesis, and the distribution of photosynthetic products, significantly impacting tomato growth and development[28]. However, excessive fertilization was also detrimental to tomato growth[4,15,55]. Moderate fertilization could significantly reduce the gaseous loss of N fertilizer to improve fertilizer utilization efficiency[56,57] for good plant growth. The two-factor interaction results in Table 1 demonstrate that W×N treatment had an extremely significant influence on RW (p<0.001) and PSW (p<0.01). The above results also indicate that over-irrigation and N application induced unreasonable biomass of different organs[52,58]. The reduced root growth would inhibit aboveground growth, particularly fruit growth[4]. In summary, a sufficient irrigating system was beneficial for promoting the development of tomato reproductive organs, and W2N2 treatment was most beneficial for the early growth of greenhouse tomato plants.

4.2 The coupling effects of W×N on SPAD and N content of tomato leaves

The SPAD value and chlorophyll content were closely related to the photosynthetic capacity and health status of plants[59-61]. Furthermore, SPAD values had a significant positive correlation with the chlorophyll content[62]. Meanwhile, the leaf moisture, temperature, and nutrient absorption were also important factors affecting leaf photosynthetic activity and plant architecture[63-65]. Ou et al.[31] found that the trend of changes in photosynthetic rate (Pn) and SPAD value of tomato leaves was consistent. Irrigation and fertilizer management could alter the physiological characteristics of tomatoes by influencing nutrient transport and balance in the plant-soil ecosystem[28]. In this article, SPAD (Figure 3), leaf RH (Figure 4b), and N content (Figure 5) had similar dynamic changes when the plant grew after transplanting. Significantly, leaf T showed different trends, but all treatments had a similar fluctuation over time (Figure 4a). In addition, the W2 treatments almost received higher T values than W1 as the plant was growing, indicating that a higher irrigating amount could improve leaf T. This might be because the leaf temperature was greatly determined by the air environment temperature, and higher irrigation could enhance heat after leaf metabolic activity. Leaf moisture (RH) is influenced by soil moisture and air humidity, as well as irrigation and nitrogen management. The SPAD changes under all W×N treatments displayed different intense up and down fluctuations, indicating that W×N coupling effects were obvious. This matched with irrigation and fertilization, which also had significant effects on SPAD at the early stages after transplanting[28]. In addition, an appropriate increased irrigation amount could increase the chlorophyll content of tomatoes and accumulation of leaf nutrients[11,18,39]. N3 application had an improved effect on leaf N content. The leaf SPAD and N contents under all W2 treatments on the 96th day after transplantation were lower than those under W1. Moreover, the values of leaf SPAD, RH, and N content stayed at a higher level under W1N3 on the 96th day after transplanting. Therefore, a low N application rate was beneficial for promoting leaf N content. Furthermore, irrigation significantly affected the effectiveness of fertilization, and the reduced irrigation could promote leaf N content under N reduction treatment. Finally, W1N3 treatment basically could improve leaf N content during most of the time after transplanting. It also reduced fertilizer input and waste, maintaining a good growth environment for plants. One report says that appropriate irrigation and fertilization were beneficial for increasing the chlorophyll SPAD value, but N application had a much greater influence on the chlorophyll content of leaves than did irrigation[11]. The two-factor interaction results also show that W had the most significant effects on leaf SPAD, T, RH, and N content (p<0.001), while only N application greatly affected SPAD value (p<0.05, Table 1). Too high of a soil moisture content under high irrigation inhibited photosynthesis[66]. Additionally, the above results might be explained with reference to their Pearson correlation results. Pearson correlation analysis demonstrates that the increased PH could greatly improve leaf SPAD and N content. However, the increasing SC and leaf T could obviously reduce N accumulation and SPAD. In addition, leaf SPAD (r=0.85) and RH (r=0.83) evidently promote N content in leaves, judging by the extremely significant positive correlations (p<0.01, Figure 7). Furthermore, RH could significantly decrease T. A high frequency of fertigation and/or irrigation increased the N uptake, guaranteed optimal crop N nutritional status even in the early stages, and promoted crop growth[67]. Therefore, the irrigation frequency might mainly affect N recovery at high N application[67].

4.3 The coupling effect of W×N on the first order tomato fruit growth and quality

Irrigation can significantly impact tomato NF[16]. In this study, the two-factor interaction results in Table 1 show that both single W, single N, and W×N treatments had no significant influence on NF and SFW. However, NF and SFW under W1 increased as N application went down, while W2 displayed the opposite phenomenon (Figure 2d). This indicates that the reduced water and N fertilizer could enhance flowering and fruit bearing, and a certain decreasing N application under higher irrigation could enhance NF (W2N2) and SFW (W2N3). It might be that the enhanced PH restrained NF (p<0.05), judging from the results of the Pearson correlation analysis in Figure 7. Meanwhile, LW might have weakly decreased SFW (r= –0.33, Figure 7).

Additionally, the irrigation system and fertilizer treatments had interactive effects on tomato fruit VC and SS[68], which were mainly used to evaluate its nutritional quality[28]. Although there were some significant differences between repetitions under some treatments, results of this study still show that the decreased N applications could improve tomato VC content, but decrease SS under water-saving irrigation (W1, Figure 6). However, adequate water supply (W2) and suitable reduced N application did reduce VC, but promoted SS. Pearson correlation analysis (Figure 7) showed leaves' SPAD could significantly impact VC (p<0.05) and extremely significantly impact SS (p<0.01), respectively. In addition, N in leaves could also significantly influence VC (p<0.05), while leaf T had an extremely significant impact on SS (p<0.01). Some research reported that the poorer soil nutrients under a water deficit could ultimately increase VC accumulation[27]. The two-factor interaction results showed that the W×N treatment only greatly affected VC value (Table 1), while only W significantly influenced SS. Moreover, PSW significantly influenced VC and SS (p<0.05), and W×N treatment greatly affected PSW value (Table 1). One study believed that SS and VC content in tomato fruit were not influenced by fertilization[35], but a former study found that N fertilizers highly significantly influenced VC and SS contents of cherry tomato[28]. The above results of SS and VC in this paper might be a little different with the former research, which also demonstrated that a single fertilizer and the interaction between irrigation and fertilizer remarkably influenced the cherry tomato fruit SS and VC content (p<0.01) [28]. This is mainly because the fertilizers used were different than those used in the former study. On the whole, applying enough N fertilizer under enough irrigation could reduce VC but improve SS. Additionally, some reduced N application under water-saving irrigation could promote SS and decrease VC to improve tomato fruit quality.

5 Conclusions

This study investigated the effects of different irrigation and nitrogen application interactive management models on plant growth, leaf physical properties, and first order fruit of cherry tomatoes, as well as their fresh biomass and quality at the first flowering and ripening stage. The results indicated that W×N had significant impacts on the early growth of tomato root, leaf and plant stem, and VC. Irrigation mainly drove the increases of plant height, stem diameter, and VC, as well as leaf SPAD, T, RH, and N contents. Meanwhile, N supply mainly affected matter formation, and then significantly influenced fresh biomass of leaf and root. Significantly, plant height, stem diameter, leaf SPAD, T, and RH were the main factors to influence N absorption in early leaves. Plant height was also an important factor affecting the number of first order fruits. PSW and SPAD significantly influenced tomato VC and SS. Among all interactive treatments, W2N2 could improve plant height (with the highest PH at 152.5 cm), stem circumference (4.1 cm), the number of first order fruits (11 fruits), and fresh leaf weight (45.0 g/plant). However, it reduced tomato VC (9.71 mg/kg) and SS (2.40%). W2N3 significantly increased leaf number (103.4 pieces/plant). W2N1 achieved the highest single fruit weight (21.3 g), root weight (14.4 g/plant), and stem weight (71.8 g/plant). W1N3 also improved the number of first order fruits (11 fruits), leaf SPAD (36.85), humidity (56.9%), and N content (14.2 mg/g), as well as VC (16.29 mg/kg). W1N1 could be the best at improving SS (4.06%). These results demonstrate that suitable reduced N input could promote early plant growth and improve the quality of cherry tomato. The study results also could provide a reference for irrigation and nitrogen interaction intelligent management systems in tomato plant and leaf growth at the early growing stage. Future research warrants attention to the plant growth, yield, and quality, as well as water and N utilization efficiency during the later growing period. Meanwhile, soil physical and chemical properties as well as microorganisms after planting tomato should be investigated to explore the mechanisms of soil-plant interactions induced by irrigation and nitrogen coupling management. Efficient irrigation and nitrogen coupling management models could also be explored from the perspective of tomato economic efficiency.

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