Effects of biofertilizer and water-saving irrigation interactions on the leaf photosynthesis and plant growth of tomatoes

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Abstract: Irrigation and fertilizer interaction is an efficient cultivation management strategy for facility agriculture. However, the effects of irrigation and fertilizer management on tomato growth and its physiological factors remain unclarified. In this study, two irrigation patterns (W1, conventional irrigation; W2, water-saving irrigation) and four fertilizer application patterns (CF, chemical fertilizer; BOF, biological organic fertilizer; NPK, nutrient compound fertilizer; BOF+NPK) were selected to observe the effects of their interaction on cherry tomato plant growth, leaf photosynthesis and fruit quality through pot experiments. The results showed that W2 treatments promoted plant height growth compared to W1 under the same fertilizer addition. Moreover, irrigation and fertilizer management had significant effects on net photosynthetic rate, intercellular oxidation concentration, stomatal conductance and transpiration rate at the first sequence flowering and fruiting stages. The maximum tomato plant height (99.0 cm) was achieved under the irrigation and fertilizer pattern of BOF and W2, along with the highest fruit yield of 1.98 kg/plant, which was approximately 31.1% higher than the minimum yield under the combined CF and W2 treatment. Under W2 treatments, the application of either NPK or BOF increased the soluble sugar content of tomatoes. The structural equation models showed that the soil alkali hydrolyzed nitrogen could directly significantly affect the yield and soluble sugar. The findings suggest that optimization of irrigation-fertilizer interactions positively regulates tomato growth, providing an efficient model for tomato irrigation and fertilizer management and a reference for sustainable development of facility agriculture.

Keywords: irrigation-fertilization interaction, cherry tomato, plant height, leaf photosynthesis, fruit yield and quality
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1 Introduction

Tomato (*Solanum Lycopersicum*) is considered to be one of the most in-demand vegetable crops and popular healthy fruits in the world[1,2]. The tomato is the second most produced vegetable crop in the world[3]. High quality, efficient and intelligent cultivation of tomatoes is a current research hotspot, whereas it also faces problems such as low irrigation and fertilizer utilization and environmental pollution. Irrigation and fertilizer directly influence tomato growth and development, yield formation and fruit quality[4-6]. Optimizing irrigation and fertilizer management helps to sustain greenhouse tomato production, achieve the "win-win" strategy of high yield and profit maximization, and reduce environmental risks caused by irrational fertilization management practices[7]. Therefore, studying the effects of chemical fertilizer reduction, organic replacement of chemical fertilizer and combined application of organic and inorganic fertilizer on tomato physiology under water-saving irrigation conditions is the key to the green development of facility agriculture[8].

Generally, tomatoes require substantial amounts of water to grow[9]. However, Nangare et al.[10] found similar economic yields of tomatoes under full and deficit irrigation. A certain lower irrigation level resulted in a significant reduction in fresh and dry weights of tomatoes, whereas 80% or 60% of field capacity did not significantly reduce the growth performance of tomatoes[11]. They found that 50% of full irrigation amount reduced yield, yet received the greatest decrease in water use efficiency. Decreased supplemental irrigation contributed to delaying the decline in the photosynthetic capacity of tomato leaves[12]. Shao et al.[13] concluded

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that 70% of field capacity improved tomato tolerance to flooding stress by reducing the increase in net photosynthetic rate (Pn), stomatal conductance (Gs) and transpiration rate (Tr). Nevertheless, they found that 80% irrigation was more detrimental to fruit quality and yield after flowering than 70% irrigation. Zhang et al.[14] suggested that 75% of water under sprinklers could improve the tomato yield and water use efficiency. Additionally, the evidence suggested that reasonable irrigation deficit increased the soluble solids, soluble sugars (SS) and vitamin C (VC) content, and conserved water to some extent[2,14,15]. Irrational irrigation systems caused vegetable pests and diseases, exacerbated soil N leaching and soil degradation, and led to the risk of non-point source pollution[16]. Therefore, greenhouse tomatoes require more precise watering and fertilisation, especially when the area of automated greenhouses is rapidly increasing[17,18].

Scientific and rational fertilization could provide essential nutrients for plant growth[19]. Nutrition management plays an important role in the yield and quality of tomatoes. For instance, the proper application of organic fertilizer and the combination of organic and chemical fertilizers significantly improved the yield and quality of tomatoes[20]. In addition, some organic F were found to obtain higher rates of large tomato fruits, increased ascorbic acid, β-carotene, total soluble solids and some organic matter[21]. However, some researchers considered SS and VC content in tomato fruit not to be influenced by fertilization[22]. The SS could be increased by adjusting the proportion of N, P and K and reducing their dosage[23]. Furthermore, the N application promoted the asexual growth and fruit yield, whereas reduced water use efficiency (WUE), soluble solids and total antioxidant capacity of tomatoes[24,25]. This was related to the fact that total N inputs were much higher than the requirements of greenhouse crops[26,27].

The interaction of irrigation and fertilizer had a combined effect on tomato growth and development[28]. Xing[29] found that irrigation and fertilizer significantly increased the single fruit weight. The water-saving irrigation and a reasonable N: P_2O_5: K_2O ratio interaction increased the dry biomass and chlorophyll content of tomatoes[30,31]. Conversely, it was suggested that irrigation and fertilizer had a negative impact on yield and irrigation use efficiency[17]. The optimal irrigation and fertilizer pattern was important for tomato quality, especially in greenhouses with elevated CO_2[32]. However, the effects of irrigation and fertilizer on plant growth and photosynthetic physiology in different periods of tomato remain unclarified.

Herein, eight fertilization and irrigation interaction treatments were selected to manage a cherry tomato plant in a pot experiment, with plant growth, photosynthesis, yield and quality of tomato investigated. Our objectives were to: 1) analyze the contribution of single irrigation and fertilizer and their coupling effect on photosynthesis; 2) study the internal relationship of tomato soil system under irrigation and fertilizer treatments; 3) obtain irrigation and fertilizer patterns beneficial for a high yield and good quality of greenhouse cherry tomato. The results will provide an important theoretical and practical significance for the realization of the high quality and efficient production of greenhouse crops and sustainable development of agriculture.

2 Materials and methods

2.1 Soil preparation

The tested soil of this study was collected from the rice-vegetable rotation field at Jiangsu Academy of Agricultural Sciences (32°03′N, 118°87′E). Soilfield capacity was 37.9%. Soil basic properties were as follows: pH 6.74; soil organic matter (SOM) of 16.88 g/kg; alkali hydrolyzed nitrogen (AN) of 61.94 mg/kg; available phosphorus (AP) of 36.83 mg/kg; available potassium (AK) of 85.83 mg/kg.

2.2 Experimental design

The pot experiments were located in the greenhouse of the Jiangsu Academy of Agricultural Sciences. The potting containers used were rectangular PVC pots measuring 38 cm in length, 20 cm in width, and with an effective depth of 50 cm. Each pot contained 88 kg of soil.

The cherry tomato 'Golden Plumfish' with high disease resistance and high yield was selected as a test target in this study. Cherry tomato seeds were obtained from the Jiangsu Academy of Agricultural Sciences. They were limited growth F1 hybrids bred from the female parent 'jsct10' and the male parent 'jsct17'[33]. Seedlings (9-10 cm in height) were transplanted on 7 September 2018, with one plant planted in each container. Fruit harvesting took place on 12 November 2018. Two irrigation systems were set up: conventional irrigation (W1, maintaining 75-100% of the soil field capacity) and water-saving irrigation (W2, 80% of the W1 irrigation). Meanwhile, four types of fertilizer application were selected: chemical fertilizer (CF, 4 g $(NH_4)_2HPO_4$, 8 g K_2SO_4 and 10 g $(NH_4)_2SO_4$ per plant), biological organic fertilizer (BOF, 100 g per plant), nutrient compound fertilizer (NPK, 15 g per plant), and a combination of BOF (50 g per plant) and NPK (10 g per plant). The BOF contained ≥20% N+P_2O_5+K_2O, ≥20% organic matter, ≥10% micronutrients, ≥2% amino acid, and ≥20 billion/g of active bacteria. The N: P_2O_5: K_2O ratio of the NPK was 15:15:15. Generally, eight irrigation and fertilizer coupling treatments were set up as CF+W1 (CW1), CF+W2 (CW2), BOF+W1 (BW1), BOF+W2 (BW2), NPK+W1 (NW1), NPK+W2 (NW2), BOF+NPK+W1 (BNW1), BOF+NPK+W2 (BNW2), as shown in Figure 1. Fertilizer was applied to the soil at once before transplanting. The first irrigation ensured that the water level was 1 cm above the topsoil. The greenhouses for planting cherry tomatoes were well lighted while ensuring that they were grown at an average monthly temperature of 20°C to 25°C. Moreover, 60-mesh insect nets were installed at the windward end of the greenhouse to avoid pest and disease problems. Other growth management was carried out according to the general measures for cherry tomatoes.

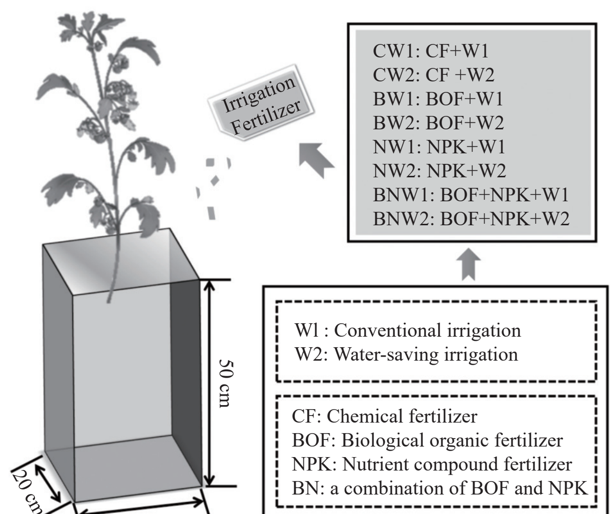


Figure 1 Methodological framework explaining the experimental design and the condition in all treatments

2.3 Plant height

Plant height (H) was obtained by measuring the distance from the roots to the top of the plant with a straight edge on 2 October (H0, day 25 after seedling transplanting), 10 October (H1, Day 33 after seedling transplanting), 18 October (H2, day 41 after seedling transplanting), 1 November (H3, Day 55 after seedling transplanting) and 12 November (H4, Day 66 after seedling transplanting), respectively.

Increments of H were calculated as follows:

$$\Delta H0\left(\text{Seedling stage}\right) = H0 - h \tag{1}$$

$$\Delta H1\left(\text{First sequence flowering stage}\right) = H1 - H0 \tag{2}$$

$$\Delta H2\left(\text{Late flowering stage}\right) = H2 - H1 \tag{3}$$

$$\Delta H3\left(\text{Fruiting stage}\right) = H3 - H2 \tag{4}$$

$$\Delta H4\left(\text{Plant topping stage}\right) = H4 - H3 \tag{5}$$

$$\Delta H = H4 - h = \Delta H0 + \Delta H1 + \Delta H2 + \Delta H3 + \Delta H4 \tag{6}$$

where, *h* means the transplant height of the seedling, cm.

2.4 Leaf photosynthetic physiological characteristics

Photosynthetic indicators were tested at early flowering and early fruiting stages with the portable photosynthesis system (CIRAS-3, Hansatech, British). These indicators included net photosynthetic rate (Pn), intercellular oxidation concentration (Ci), stomatal conductance (Gs), transpiration rate (Tr) and instantaneous leaf water use efficiency (IWUE). Chlorophyll fluorescence values (SPAD) were observed by a Chlorophyll fluorometer (TYS-4N, Top Cloud-Agri, China). The tested leaves were selected according to the steps in the study by Li et al.[34].

2.5 Fruit yield and quality

Tomato fruits were harvested to calculate the yield. Ripe fruits were washed with distilled water and then polished to a pulp for the determination of SS and VC. The contents of SS and VC were determined by the anthrone colorimetry method and the molybdenum blue colorimetry method[9,35,36], respectively.

2.6 Statistical analysis

Data and diagrams were organized and drawn using Microsoft Excel 2021. Statistical differences (p<0.05) among individual treatments were measured using Duncan's multiple comparison tests (One-way ANOVA) in IBM SPSS Statistics v.17.0 (IBM Corp., Armonk, NY, USA). Two-way ANOVA was used to analyze the effects of irrigation, fertilizer and their interaction on leaf photosynthesis, fruit yield and quality.

3 Results

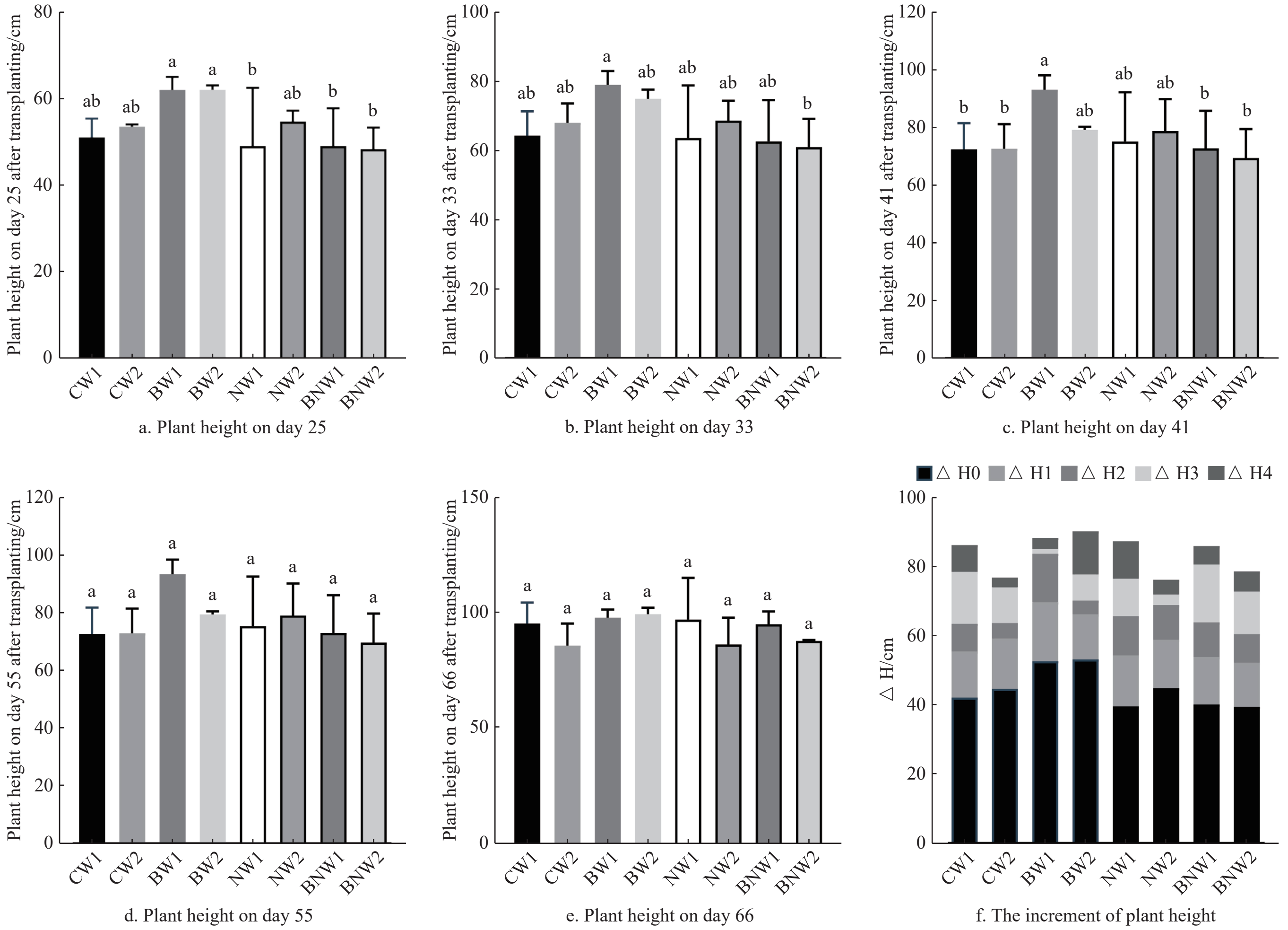
3.1 Response of plant height to irrigation and fertilizer management

Plant height was an important index to reflect crop growth and drought resistance (Figures 2a-2e). In this study, W2 could improve the height of tomatoes on day 25 after transplanting at the late seedling stage. A similar trend popped on days 25, 33 and 41 after transplanting. The treatments of BW1, BW2 and NW2 received the top heights, while CW1, NW1, BNW1 and BNW2 got the lowest values. Moreover, W1 still got the highest H3 on day 55 after transplanting, whereas BNW1 got a faster increment of plant height (ΔH) followed by CW1. Before topping on day 66 after transplanting, BW2 significantly got the largest plant height (H4=99.0cm, p<0.05), next to BW1 (H4=97.5cm) and NW1 (H4= 96.7cm). Remarkably, CW2, NW2 and BNW2 had H4 obviously below 90.0 cm (p<0.05). The ΔH0 increased under W2 at the same fertilization (Figure 2f). In the same watering system, BOF met with the largest ΔH0. Furthermore, there was no evident difference between NPK and CF treatments, while BOF+NPK obtained the lowest increment. The order of ΔH0 showed with a sequence as BW2≈BW1>NW2≈CW2>CW1>BNW1>NW1≈BNW2. As the tomato plant grew, all values of ΔH1 by treatments (except CW1 and BNW1) were higher than their late ΔH. BW1 received the highest ΔH1 and ΔH2. However, BNW1 showed the largest ΔH3 followed by CW1, BNW2 and NW1. It was noteworthy that BW1 got no increment from 18th October to 1st November. Subsequently, BW2 had the biggest ΔH4 followed by NW1. Summarily, the increment of plant height after transplanting (Figure 2f) showed the largest ΔH presented in BW2 at 90.0 cm, followed by BW1 (88.0 cm), NW1 (87.2 cm), CW1 (86.0 cm), BNW1 (85.7 cm), BNW2 (78.5 cm), CW2 (76.5 cm) and NW2 (76.0 cm).

3.2 Photosynthetic physiology

Water stress significantly influenced tomato photosynthesis. Treatments except for CW1, CW2, and NW1 received higher Pn and Ci in the first flowering period (H1) (Figure 3a). On H1, BNW1 got the evident highest Pn at 33.78 μmol/(m^2·s) (p<0.05), while NW2, BW1 and NW1 had the lowest ones. At the early fruiting stage (H3), NW1 had an obvious highest Pn at 27.01 μmol/(m^2·s) (p<0.05). The Pn under CW1, CW2, BW1 and BNW2 were no more than 9.53 μmol/(m^2·s), and the rest treatments were lower than 13.00 μmol/(m^2·s). As for Ci, BNW1 significantly displayed the lowest value at 130.89 mg/L (p<0.05, Figure 3b) on H1, while CW1 (174.89 mg/L), BW1 (174.25 mg/L), CW2 (172.51 mg/L) and BNW2 (171.50 mg/L) got far more values. BW2 (67.04 mg/L) and BNW1 (87.74 mg/L) demonstrated the obvious lowest values on H3 (p<0.05). However, Ci under all CF treatments got much more than others. Each treatment received a lower Gs value on H3 than that on H1 (Figure 3c). On H1, CW2 had the biggest Gs at 344.2 mmol/(m^2·s), followed by NW2 [325.2 mmol/(m^2·s)], BNW1 [311.0 mmol/(m^2·s)] and BW2 [298.7 mmol/(m^2·s)]. They surpassed the smallest values of BNW2 [230.0 mmol/(m^2·s)] and BW1 [236.0 mmol/(m^2·s))] (p<0.05). On H3, NW1 got the significant largest Gs at 207.9 mmol/(m^2·s) (p<0.05), followed by BW2 [159.8 mmol/(m^2·s)]. These Gs values of rest treatments were all below 90.0 mmol/(m^2·s). All treatments received lower Tr values on H3 than that on H1 (Figure 3d). BNW1 got the largest value at 7.7 mmol/(m^2·s), obviously surpassing CW1, BW1, NW1, NW2 and BNW2 (p<0.05). Remarkably, Tr values treated by CF or BOF under W1 were bigger than those under W2. On H3, NW1 had an obvious largest Tr at 4.4 mmol/(m^2·s) (p<0.05). BW1 got the second largest Tr at 2.9 mmol/(m^2·s), significantly surpassing the rest (p<0.05).

The IWUE showed an obvious difference between BW1 and BW2 (p<0.05, Figure 3e). Both had no significant difference from the rest treatments (p<0.05). Except for CF treatments, others demonstrated a bigger IWUE on H3 than that on H1. Both BW2 and CW2 received the largest IWUE at 4.4% on H1. The IWUE at the fruiting stage displayed the biggest first and second values under BNW1 (5.87%) and BW2 (5.80%), followed by NW1, BNW2, NW2, BW1, CW1 and CW2. BW2 had the highest SPAD at 52.07 (p<0.05, Figure 3f) on H1 when the first flower was blooming, followed by NW2 (46.27) and BNW1 (45.84). The treatments of BNW2 (36.51) and CW1 (35.50) got the lowest values. As the first order fruits grew on H3, BW2 still obtained the highest SPAD at 58.97, significantly surpassing the lowest value of CW1 (30.70). The highest SPAD was presented in BNW1 (58.83) and BW1 (50.93).



Note: Different lowercase letters represent significant differences (p<0.05, n=3). CW1: chemical fertilizer with conventional irrigation; CW2: chemical fertilizer with water-saving irrigation; BW1: biological organic fertilizer with conventional irrigation; BW2: biological organic fertilizer with water-saving irrigation; NW1: nutrient compound fertilizer with conventional irrigation; NW2: nutrient compound fertilizer with water-saving irrigation; BNW1: a combination of biological organic and nutrient compound fertilizer with conventional irrigation; BNW2: a combination of biological organic and nutrient compound fertilizer with water-saving irrigation. ΔH0: Seedling stage; ΔH1: First sequence flowering stage; ΔH2: Late flowering stage; ΔH3: Fruiting stage; ΔH4: Plant topping stage.

Figure 2 Plant height of different irrigation and fertilizer treatments

The variance analysis results displayed that irrigation very significantly influenced Gs at the two stages (p<0.01, Table 1), with very significant impacts on Pn and Tron H3 (p<0.01). Fertilization very significantly impacted Pn at the two stages (p<0.01). On November 1st, fertilization extremely significantly influenced Ci, Gs and Tr (p<0.01), with an obvious effect on SPAD (p<0.05). Furthermore, irrigation and fertilization had significant (p<0.05) or extremely significant impacts (p<0.01) on Pn, Ci, Gs and Tr at the two stages, with a significant impact on SPAD on H3 (p<0.05). Significantly, there were no significant impacts of irrigation, fertilization or their interaction on IWUE each time.

Table 1 Significant effects of irrigation, fertilization and their interaction on different photosynthetic physiological indexes

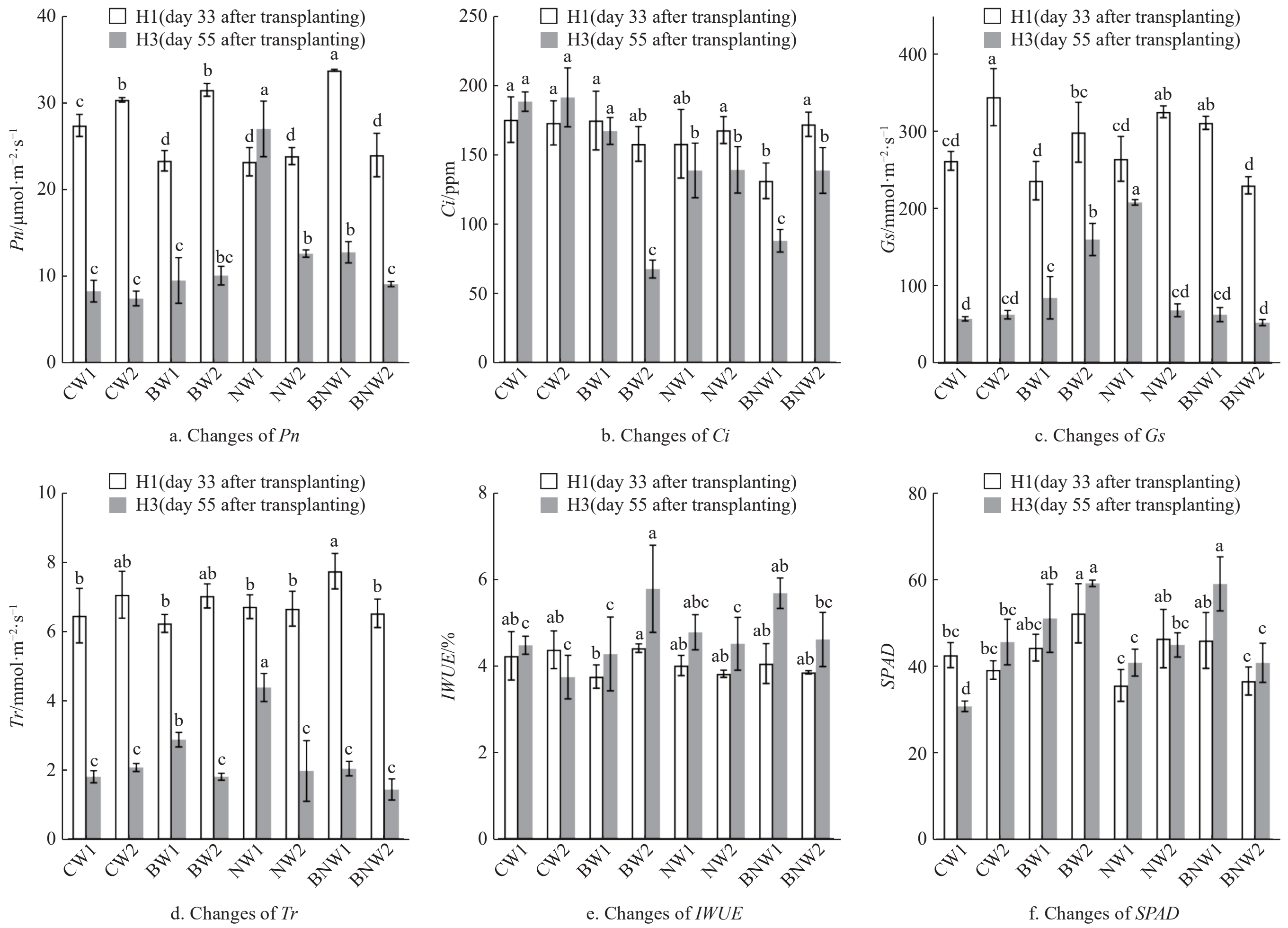
Indexes	Pn		Ci		Gs		Tr		IWUE		SPAD	
	H1	H3	H1	H3	H1	H3	H1	H3	H1	H3	H1	H3
Irrigation	ns	**	ns	ns	**	**	ns	**	ns	ns	ns	ns
Fertilization	**	**	ns	**	ns	**	ns	**	ns	ns	ns	*
Irrigation×Fertilization	**	**	*	**	**	**	*	**	ns	ns	ns	*

Note: **and *displayed extremely significant differences at 1% and 5%, respectively. The ns displayed no significant difference. H1 represents day 33 after transplanting; H3 represents day 55 after transplanting. Pn: net photosynthetic rate; Ci: intercellular oxidation concentration; Gs: stomatal conductance; Tr: transpiration rate; IWUE: instantaneous leaf water use efficiency; SPAD: Chlorophyll fluorescence values.

Pearson correlation analysis (Figure 4) demonstrated that the Pn had a significant positive correlation with Gs and IWUE (p<0.05) on H1, respectively. Pn also had a very significant positive correlation with Tr (p<0.01), but a significantly negative correlation with Ci (p<0.05). On H3, Pn just extremely significantly correlated with Gs and Tr (p<0.01), respectively. Moreover, Ci had a significant negative correlation with IWUE and SPAD (p<0.01) on November 1st. Noticeably, Gs also obtained a significant positive correlation with Tr (p<0.01) on H1 and H3. IWUE showed a significant positive correlation with SPAD (p<0.01).

3.3 Yield and quality

The yield (Y), vitamin C (VC) and soluble sugar (SS) were the main factors for tomato production. All W2 treatments improved the yield, SS and VC more than W1 (Figure 5). Tomato treated by BW2 and BNW2 received the significant largest yield at1. 98 kg/plant (p>0.05), about 131.13% of the minimum value under CW2. The following yields were NW2 (1.89 kg/plant) and BW1 (1.84 kg/plant). The SS contents under different I-fertilization treatments presented a significant difference (p<0.05, Figure 5). NW2 received the obvious highest SS at 73.04 g/kg, followed by BW2 (71.28 g/kg) and BNW2 (68.18g/kg). The rest of the treatments got lower SS contents(p<0.05). The VC contents under all CFs surpassed the rest treatments (p<0.05). The VC values under



Note: The lowercase letters in the same color column indicate that the difference between treatments was significant at the level of 0.05 in each figure. CW1: chemical fertilizer with conventional irrigation; CW2: chemical fertilizer with water-saving irrigation; BW1: biological organic fertilizer with conventional irrigation; BW2: biological organic fertilizer with water-saving irrigation; NW1: nutrient compound fertilizer with conventional irrigation; NW2: nutrient compound fertilizer with water-saving irrigation; BNW1: a combination of biological organic and nutrient compound fertilizer with conventional irrigation; BNW2: a combination of biological organic and nutrient compound fertilizer with water-saving irrigation; Pn: net photosynthetic rate; Ci: intercellular oxidation concentration; Gs: stomatal conductance; Tr: transpiration rate; IWUE: instantaneous leaf water use efficiency; SPAD: Chlorophyll fluorescence values.

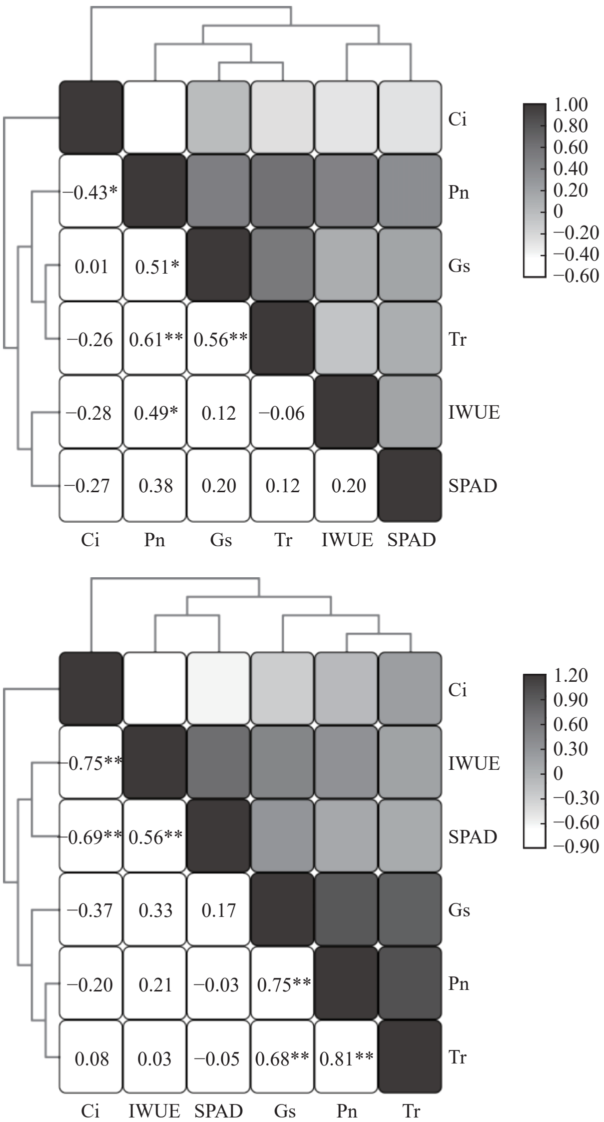
Figure 3 Photosynthetic physiology under irrigation-fertilizer treatments

BOF were the lowest (< 5.80 mg/kg), with a higher value under W1. CW2 and CW1 got the first and second largest values of VC at 9.41mg/kg and 8.78mg/kg, respectively. The variance analysis demonstrated single fertilizer and combined irrigation and fertilizer remarkably influenced tomato yield (p<0.01). However, irrigation, fertilizer and their interaction remarkably influenced its SS (p<0.01), while fertilizer impacted highly significantly influenced VC (p<0.05).

4 Discussion

4.1 Effects of irrigation-fertilization coupling on leaf photosynthetic physiology

Moisture stress significantly affects crop photosynthesis (e.g., Pn, Tr and Gs), which in turn affects the accumulation, transportation and distribution of photosynthetic products and alters the formation of plant biomass[37]. However, Ding et al.[38] concluded that maintaining high soil moisture to a certain extent was crucial to maintaining high photosynthetic capacity in tomatoes, which decreases rapidly at soil field moisture below 70%. Under different irrigation limits and fertilization rates, tomato yield had a significant linear correlation with leaf Pn, and IWUE was quadratically and parabolically correlated with Pn[39]. In this study, treatments except NW1 received the lower Pn in H3 compared to H1, with BNW1 getting the evident highest value (Figure 3). The main reason for the decrease in Pn might be stomatal limitation[40]. The Gs and Tr values of each treatment were lower at the H3 stage than at the H1 stage (Figure 3). One possible explanation is that the longer period of alternating water and N stimulation caused the soil to deliver higher abscisic acid signals to the leaves, inducing stomatal closure and reducing Tr[41]. On H1, CW2 had the biggest Gs, a little higher than NW2, BNW1 and BW2. On H3, NW1 got the significant largest Gs (Figure 3). Cheng et al.[42] earlier found that the water stress significantly reduced the Gs of tomato leaves. However, our results showed that water-saving irrigation increased tomato Gs, which might be related to the increase in stomatal aperture and Ci[43]. Moreover, we found that IWUE was greater on H3 than on H1 for all fertilizers except CF (Figure 3). Although different treatment factors regulate leaf WUE by different mechanisms, the application of non-chemical fertilizers could improve leaf-scale IWUE[44]. SPAD values were used to reflect the chlorophyll content as there was a significant positive correlation between the two[45]. BW2 had the largest IWUE and SPAD values at both the H1 and H3 stages. This confirmed the positive role of BOF in promoting crop growth. The large amount of available C sources in BOF may increase the



Note: H1 represents day 33 after transplanting; H3 represents day 55 after transplanting. Pn: net photosynthetic rate; Ci: intercellular oxidation concentration; Gs: stomatal conductance; Tr: transpiration rate; IWUE: instantaneous leaf water use efficiency; SPAD: Chlorophyll fluorescence values. * and **displayed extremely significant at 5% and 1%, respectively.

Figure 4 Pearson correlation analysis of photosynthetic physiological indexes of tomato under different irrigation-fertilizer treatments (n=24)

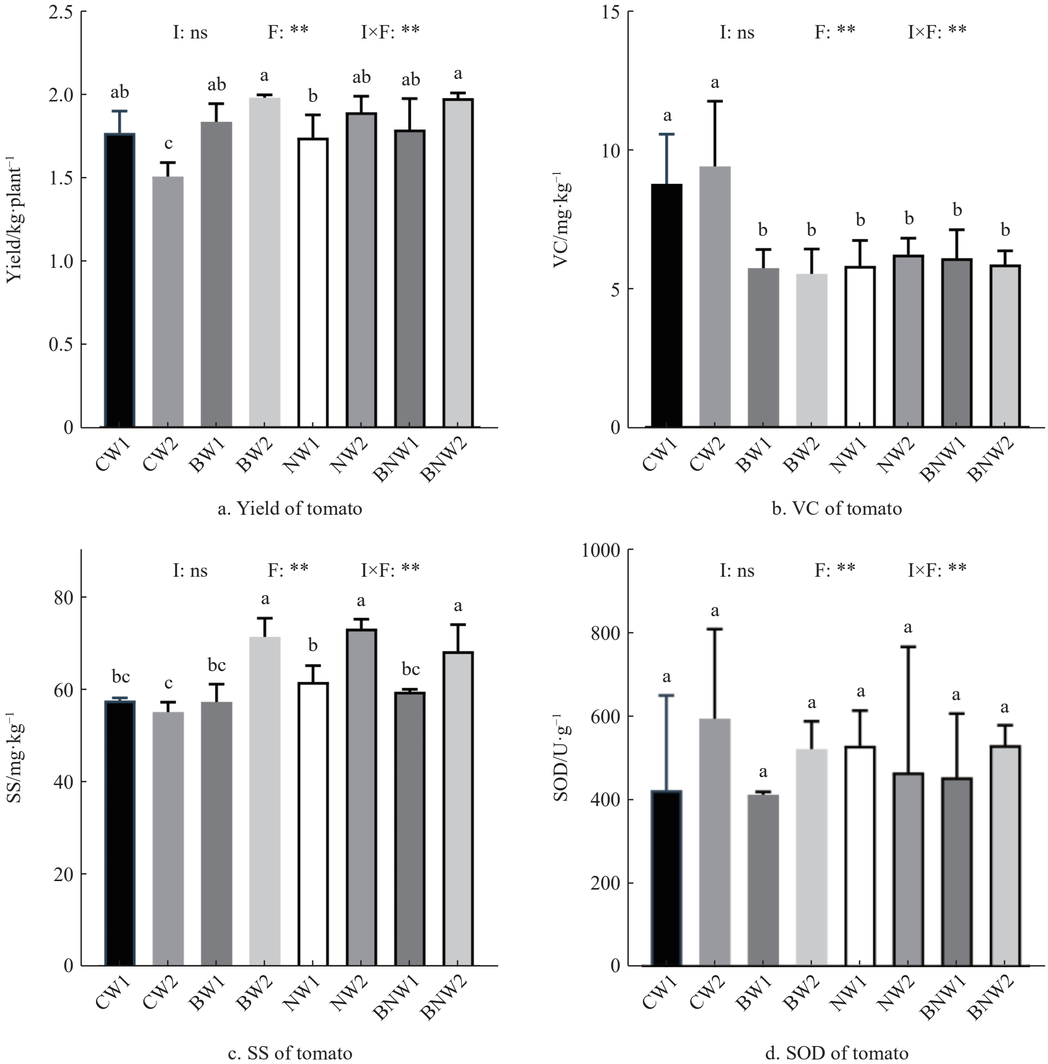
abundance of beneficial microbial communities, and improve the soil C and N conversion function, thereby providing more water and nutrients to the plant system through roots[46].

Irrigation and fertilizer had interactive effects on the photosynthetic physiology of tomato leaves (Table 1). The results displayed that irrigation and fertilization had significant and obvious impacts on Pn, Ci, Gs and Tr at the H1 and H3 stages. Irrigation and fertilization also had significant effects on SPAD in H3. Irrigation had an extremely significant effect on Gs in H1. Meanwhile, fertilization significantly influenced Ci, Gs and Tr in H3, with an obvious effect on SPAD. Notably, there was no statistically significant effect of irrigation, fertilization, or their interactions on IWUE. Therefore, an important issue regarding the promotion of crop photosynthesis by regulating irrigation and fertilization is to optimize the timing of irrigation and fertilization strategies while ensuring IWUE, and to determine the critical thresholds at which crop Pn may undergo a jump change.

4.2 Effects of irrigation-fertilization coupling on fruit yield and quality

Plant H was an important index to reflect crop growth and drought resistance. Xing[29] found a significant positive correlation between H and aboveground dry matter quality with different change trends in the growth period. In particular, water stress could decrease tomato plant height at the late seedling stage[47]. However, the increasing N application could enhance tomato plant height[48]. This study found rational fertilization could decrease the reduced growth potential of water stress. During the seedling growth period, H0 and H1 were increased only by fertilization. It showed that water-saving could improve tomato H at the late seedling stage (Figure 2). During the early period, all BOF treatments and NPK under W2 received the top heights (Figure 2). Moreover, W1 could improve H under BOF at the early stage, but W2 could significantly increment H before topping. It was due to receive no increment under BW1 from 18th October to 1st November. Nevertheless, the long-term water stress increased H to resist adversity. Remarkably, NPK or its interaction with BOF did not improve H at the late stage because of their lower H increment under W2. In addition, leaves Pn and IWUE at the flowering stage showed to be the highest (Figure 3), when tomatoes with vegetative growth carried out photosynthesis to absorb many nutrients. These nutrients in NPK and CF fertilizers were more readily available for uptake than BOF fertilizers. Its induced soil nutrient enrichment in the short term, the plant was able to absorb more water and nutrients into the xylem[49]. Therefore, CF or NPK might be the main driving factor of H in the early growth stage. The cherry tomato ‘Golden Plumfish’ was reported with about 1.88 kg per plant under adequate irrigation and fertilizer management[33]. However, this study demonstrated that W2 could enhance the yield of this tomato (Figure 5). Correlation analysis demonstrated fertilizer and combined irrigation and fertilizer showed extremely significant effects on yield. The results showed that BOF and BOF+NPK under W2 interaction significantly increased tomato yield. The reason might be that BOF made the soil N supply relatively coordinated, and closer to crop nutrient demand. Overusing N and soil irrigation deficit decreased the biomass of tomato seedlings. Additionally, the decreased Tr at the late stage (Figure 3) might inhibit nutrient transportation and conduction, resulting in reduced dry matter accumulation, and also block tomato fruit expansion to decrease fruit weight and yield.

Fruit VC and SS were mainly used to evaluate tomato fruit’s nutritional quality. In this paper, most W2 treatments improved SS and VC more than W1. It might be due to the poorer soil nutrients under deficit water, which decreased the leaf’s number to develop the fruit, with reduced light absorption, finally increasing VC accumulation[2]. Furthermore, different irrigation and fertilizer coupling treatments had different effects on the VC and SS contents of tomato fruit[50]. VC under all CF surpassed the rest treatments, with the lowest under BOF. The SS contents showed a significant difference under different irrigation and fertilizer treatments (Figure 5). SS contents under all CF treatments were significantly lower. The variance analysis demonstrated irrigation, fertilizer and their interaction remarkably influenced the SS of tomato, while only fertilizer highly significantly influenced VC. It demonstrated the irrigation and fertilizer interaction affected on SS of this cherry tomato, consistent with a former study[51]. Overall, the water-saving irrigation and bio-fertilizer interacted treatment had the best effects on reducing VC content and increasing SS content.



Note: The lowercase letters in the same column indicate that the difference between treatments was significant at the level of α=0.05. **and *displayed extremely significant differences at 1% and 5%, respectively. The ns displayed no significant difference. CW1: chemical fertilizer with conventional irrigation; CW2: chemical fertilizer with water-saving irrigation; BW1: biological organic fertilizer with conventional irrigation; BW2: biological organic fertilizer with water-saving irrigation; NW1: nutrient compound fertilizer with conventional irrigation; NW2: nutrient compound fertilizer with water-saving irrigation; BNW1: a combination of biological organic and nutrient compound fertilizer with conventional irrigation; BNW2: a combination of biological organic and nutrient compound fertilizer with water-saving irrigation; VC: vitamin C; SS: soluble sugar; SOD: Superoxide Dismutase. I: effects of irrigation; F: effects of fertilization; I×F: effects of irrigation-fertilization interaction.

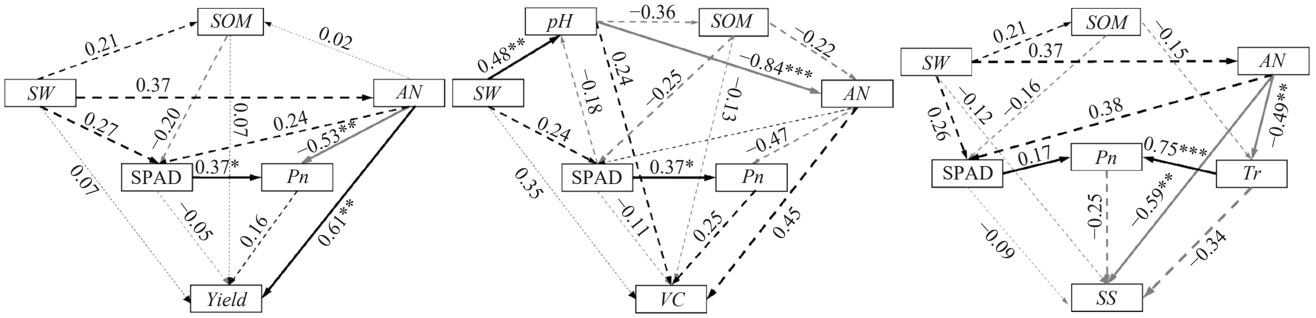
Figure 5 Yield and quality of tomato under different irrigation-fertilization treatments and their variance analysis

4.3 Research insights and perspectives

Soil properties (e.g., pH, SOM and AN), photosynthetic indexes, yield and quality well matched the hypothetical models. The results revealed that neither soil properties nor photosynthetic index had direct and significant effects on VC, nevertheless, soil AN had significant relationships with yield and SS (Figure 6). This demonstrates soil AN to be an important factor affecting tomato yield and SS. It is worth noting that increased SOM did not show a significant correlation with Y, inconsistent with most studies that suggested that SOM facilitated increased crop Y[52,53]. This reinforces the importance of irrigation and fertilizer management for tomatoes. Notably, irrigation and fertilizer management can alter the physiological characteristics of tomatoes by influencing nutrient transport and balance in the plant-soil ecosystem, while affecting fruit yield and quality. Understanding the effects of irrigation and fertilizer management on soil nutrients, crop growth and their intrinsic linkages helps to rationally assess the value of irrigation and fertilizer management strategies, and merits further exploration.

5 Conclusions

This study investigated the effects of different irrigation and fertilizer intercropping management on leaf physiological characteristics and fruit yield of tomatoes. The results indicated that chemical or compound fertilizers drove plant height increase mainly in the early stages. The organic fertilizer and water-saving irrigation treatments were the most effective in boosting tomato plant height, whereas plant growth potential under these treatments was mainly at the seedling and later stages. Additionally, the coupling of biofertilizer under water-saving irrigation promoted leaf photosynthesis in cherry tomato ‘Golden Plumfish’. Furthermore, this irrigation and fertilizer intercropping management increased tomato yield to 1.98 kg/plant and the soluble sugar content of tomatoes. Soil available N was the direct reason to influence yield and soluble sugar. The study results can provide a reference for irrigation and fertilizer intercropping management systems in intelligent tomato production. Future research warrants attention to



χ^2=0.114; df=2; P=0.945; GFI=0.998; AIC=38.114; RMR=0.011; SRMR=0.000

a. The structural equation model of Yield

χ^2=0.282; df=2; P=0.868; GFI=0.997; AIC=52.282; RMR=0.068; SRMR=0.000

b. The structural equation model of VC

χ^2=1.554; df=3; P=0.670; GFI=0.982; AIC=51.554; RMR=0.231; SRMR=0.000

c. The structural equation model of SS

Note: The solid and dashed arrows represent whether two factors have a significant relationship or not. The numbers above the arrows are path coefficients (λ). SOM: soil organic matter; AN: alkali hydrolyzed nitrogen; SPAD: chlorophyll fluorescence value; Pn: net photosynthetic rate; Tr: transpiration rate; SS: soluble sugar. *, ** and ***displayed extremely significant at 5%, 1% and 0.1%, respectively.

Figure 6 The structural equation models of Yield, VC and SS

the changes in the structure and function of soil microbial communities to explore the mechanisms of soil-microbial-plant interactions induced by irrigation and fertilizer intercropping management. Efficient irrigation and fertilizer intercropping management models can also be explored from the perspective of economic efficiency.

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