water

Article

Effects of Water and Nitrogen Coupling on Growth, Yield and Quality of Greenhouse Tomato

Wenjun Yue, Linsong Liu, Si Chen, Yu Bai and Ningyu Li *

Key Laboratory for Technology in Rural Water Management of Zhejiang Province, Zhejiang University of Water Resources and Electric Power, Hangzhou 310018, China
* Correspondence: liny@zjweu.edu.cn; Tel.: +86-571-86929060

Abstract: Irrigation water is essential for greenhouse plants because it is the only water source in the greenhouse. In addition, escalating water costs and expensive fertilizers have raised concerns about adopting advanced technology to improve water and nitrogen utilization efficiency. This study aimed to explore the effects of different water and nitrogen application rates on yield, fruit quality, and water and nitrogen utilization efficiency in southeast China. Plants were irrigated every 7–10 days at different proportions of crop evapotranspiration (ET_c) based on the modified Penman–Monteith formula (ET_0). The crop coefficient (K_c) was adopted as 0.6, 1.15, 1.15 and 0.9 during the seedling stage, flower stage, the mid-season stage and the end of the season stage, respectively. There were three water levels—0.75 ET_c (W_1), 1.0 ET_c (W_2), 1.25 ET_c (W_3)—and four nitrogen levels—120 (N_1), 220 (N_2), 320 (N_3), and 420 kg N hm^{-2} (N_4)—and a total of 12 treatments, with the application completely randomized by using block design in the experiment. Tomato yield was improved by nitrogen supply. However, nitrogen application had a negative effect on tomato yield when the nitrogen level was applied above 320 N ha^{-1}. The maximum water use efficiency (*WUE*) value of 30.5 kg m^{-3} was observed at W_2N_3, and the maximum nitrogen use efficiency (*NUE*) value of 684.4 kg kg^{-1} N was observed at W_1 treatment with N_1. The net photosynthetic rate of tomato leaves could be increased by reasonably increasing water and nitrogen application. The dry biomass increased with the amount of water and nitrogen in the range of (0.75–1.0) ET_c and (120–320) kg ha^{-1}. The best values of tomato quality parameters (Vc, Lycopene, soluble protein et al.) were observed at W_2N_3. The irrigation level of 1.0 ET_c and nitrogen level of 320 N ha^{-1} was recommended as the best combination of water and nitrogen for greenhouse tomato cultivation in the experimental areas.

Keywords: greenhouse; tomato; yield; utilization efficiency of water and nitrogen; net photosynthetic rate; quality

check for updates

Citation: Yue, W.; Liu, L.; Chen, S.; Bai, Y.; Li, N. Effects of Water and Nitrogen Coupling on Growth, Yield and Quality of Greenhouse Tomato. *Water* **2022**, *14*, 3665. https://doi.org/10.3390/w14223665

Academic Editor: Giuseppe Oliveto

Received: 30 September 2022
Accepted: 8 November 2022
Published: 14 November 2022

1. Introduction

Tomato (*Solanum lycopersicum* L.) is a popular, horticultural fruit around the world. It is a beautiful color and boasts a delicious fruit with nutrition and medicinal values [1]. Tomatoes are good for our health and provide us with provitamins, lycopene, and vitamin C [2–4]. Therefore, different varieties of tomatoes have been welcomed by consumers worldwide, and some effective measures are being taken to improve the yield and quality of tomatoes [5,6]. Facility agriculture has attracted great interest because of climate control and drip irrigation, allowing for increased production as well as saving water and fertilizer. It can improve effective light interception, leading to a higher yield than in an outdoor environment [7].

An increasing population and a higher living standard in China have promoted vegetable and fruit production, particularly in greenhouse systems [8]. It is elementary to build a greenhouse that has a simple structure. It is inexpensive to maintain because it does not require any additional energy to heat [9], and solar radiation can be efficiently used to heat it [10–12]. The greenhouse has become a steadily growing agricultural production sector in most parts of China for vegetable and fruit production the whole year round. It has provided a lot of fruit and vegetables, bringing great benefits to the local farmers.

Irrigation and nitrogen are two major restricting factors for tomato production. Irrigation water is vital for greenhouse plants because it is the only source of water in the greenhouse. Tomato is a water-demanding crop [13]. However, water is a scarce resource in many cultivation regions. The competition for water between agriculture and industry has prompted the continuous improvement of irrigation techniques in tomato cultivation. Drip irrigation has been well applied in irrigation systems because irrigation water can be delivered to the plant root zone [14]. Some researchers have found that tomato is sensitive to water deficit [15,16]. Insufficient irrigation will cause smaller fruits and low yields [17]. Therefore, it is critical for tomatoes' high production and water saving to provide an optimum irrigation schedule [18].

Among the significant plant nutrients, nitrogen (N) is the primary nutrient input to greenhouse vegetables during their growth, development, and productivity. Farmers often use plenty of N fertilizer to maximize yields [19], which has led to lower yield, poor quality, and potential threats to the ecosystem and the sustainability in the field due to N leaching. Therefore, improved N management is urgently required for vegetable production in the greenhouse. In order to achieve sustainable plant cultivation, many researchers have reported that fertilizer use efficiency could be improved by drip fertigation systems [20–23]. Previous studies have reported the effects of irrigation and nitrogen on various greenhouse plants, i.e., cucumber [24], eggplant [25], and muskmelon [26]. However, few papers have studied the effects of combining water applied in drip irrigation systems with varying nitrogen levels on tomatoes' growth, yield, and quality under greenhouse conditions.

The objective of this paper, an experiment with one commercial tomato, 'Changfeng No.5′, was carried out to explore the effects of three levels of irrigation water and four levels of nitrogen on the growth, fruit yield, quality, *NUE*, and *WUE* of greenhouse tomatoes. This study determines the optimal irrigation and nitrogen management strategy to ensure the high yield and good quality of local greenhouse tomatoes.

2. Materials and Methods

2.1. Site Description

A tomato experiment was performed in 2021 at Yangdu town in Jiaxing, China, where a very suitable private farm (108.40′ longitude, 34.18′ latitude) was chosen. The experimental area has a north subtropical monsoon climate. The annual average temperature is 15.9 °C, the annual average evaporation is 800 mm, the annual average precipitation is 1187 mm, and frost-free is about 230 days. The test results of soil types and fertility are shown in Table 1.

Table 1. Soil characteristics of the experiment site.

Soil Depth (cm)	Soil Density (g cm^{-3})	Field Capacity (Vw)	PH (dsm^{-1})	Total Nitrogen g kg^{-1}	Available *p* mg kg^{-1}	Available *k* mg kg^{-1}	Organic g kg^{-1}	Soil Texture
0–20	1.48	24.31	6.5	1.1	74.3	131.2	17.8	Sandy-loam

2.2. Plot Layout

Tomato plants were cultivated in the wide-narrow row planting pattern (0.8 m + 0.4 m), with two rows per plot (Figure 1). Each experimental plot was 6.4 m long and 1.2 m wide. The drip irrigation system was fixed after the experimental area was plowed and bedded. Two drip tubes were placed on the raised bed. There was a 100 cm deep plastic film between plots to block water and nutrients from spreading laterally. Two rows of tomato seedlings with a spacing of 40 cm were evenly transplanted on the soil bed, resulting in a planting density of 41,666 plants per hectare. The whole soil bed was covered with white plastic mulch to improve soil temperature and reduce soil evaporation.

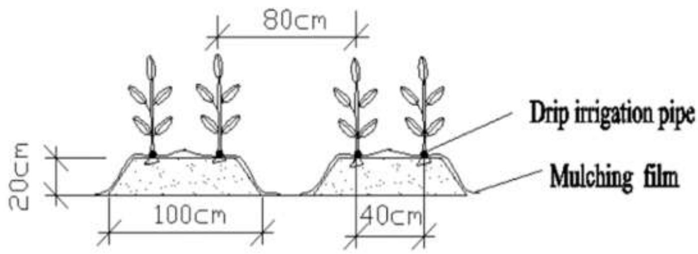

Figure 1. Layout of drip irrigation pipe, tomato-cropping pattern.

2.3. Experimental Treatments

The irrigation amount was determined using the modified Penman–Monteith formula. There were three irrigation levels (75% (W_1), 100% (W_2), and 125% (W_3) of ET_c at the 5–7-day intervals) and four N levels (120 (N_1), 220 (N_2), 320 (N_3) and 420 (N_4) kg N ha^{-1}). There were a total of 12 treatments; each treatment had three replicates.

2.3.1. Irrigation Application

Each treatment had a flow meter to monitor the irrigation water amount. Drip irrigation amount was determined from crop evapotranspiration (ET_c) using the equation $ET_c = ET_0 \times K_c$ [27]. The reference crop evapotranspiration (ET_0) was estimated by the modified Penman–Monteith equation using daily weather data from a mini-meteorological station inside the greenhouse [28]. The weather station measured air temperature, relative humidity, solar radiation et al., which were logged every 5 s and a 20 min average was calculated and stored. Crop coefficient (K_c) was adopted as 0.6, 1.15, 1.15, and 0.9 during the seedling stage, flower stage, mid-season stage, and end of the season stage according to FAO56, respectively.

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{1713}{T+273}(e_a - e_d)}{\Delta + 1.64\gamma} \quad (1)$$

2.3.2. Nutrient Application

All of the phosphorus (220 kg P_2O_5 ha^{-1}) and potassium sulfate (320 kg K_2O ha^{-1}) were applied to the soil before transplanting tomato seedlings. In addition, 30,000 kg ha^{-1} of decomposed organic fertilizer was added to the experimental plots. During the growing season, the total N fertilizer under different treatments was applied as urea, which dissolved in the irrigation water of a fertilizer tank. Nitrogen solution was injected into the main pipe of the drip system. N fertilizer was applied at 10–15-day intervals in 10 equal doses of nitrogen according to nitrogen levels in different treatments (Table 2).

2.3.3. Plant Management

The tested crop was Changfeng No. 5, a local variety of tomato. The experiment was conducted in 2021. No crops were planted before the experiment. After three days of sprouting, tomato seeds were sown in cultivating trays. The seedlings were transplanted to the soil bed and covered with a plastic film when three true leaves appeared. The seedling period is about 30 days, the whole growth circle of the tomato is about 130 days. Plant protection measures were conducted as necessary.

Table 2. Nitrogen application and irrigation amount in each growth period.

Treatment	Nitrogen Rate (kg hm^{-2})	Irrigation Amount (mm)	Irrigation Amount during Each Growth Period (mm)				
			Seedling Stage	Flowering and Fruiting Stage	Full Bearing Stage	Late Development Stage	Total
W_1N_1	120	0.75 ET_c	32	50	104.4	43.9	230.2
W_1N_2	220	0.75 ET_c	32	50	104.4	43.9	230.2
W_1N_3	320	0.75 ET_c	32	50	104.4	43.9	230.2
W_1N_4	420	0.75 ET_c	32	50	104.4	43.9	230.2
W_2N_1	120	1.0 ET_c	42.6	66.7	139.2	58.5	307
W_2N_2	220	1.0 ET_c	42.6	66.7	139.2	58.5	307
W_2N_3	320	1.0 ET_c	42.6	66.7	139.2	58.5	307
W_2N_4	420	1.0 ET_c	42.6	66.7	139.2	58.5	307
W_3N_1	120	1.25 ET_c	53.3	83.4	173.9	73.1	383.7
W_3N_2	220	1.25 ET_c	53.3	83.4	173.9	73.1	383.7
W_3N_3	320	1.25 ET_c	53.3	83.4	173.9	73.1	383.7
W_3N_4	420	1.25 ET_c	53.3	83.4	173.9	73.1	383.7

2.4. Measurements and Calculations

2.4.1. Net Photosynthetic Rate (Pn)

Leaf net photosynthetic rate (Pn) was measured by using an LI-6400 portable gas-exchange system (LI-COR, Lincoln, NE, USA). In each measurement activity, three tomato plants of uniform growth were selected representatively for each treatment. The most recently fully expanded leaf (fifth from the top) was used for the measurements. Pn was determined during the morning of a clear day with few clouds for the full fruit-bearing stage from 9:00 to 11:00. Each leaf was measured three times, and the mean value was calculated.

2.4.2. Dry Biomass, Yield, and Quality

Three tomato plants were selected as plant samples at the final harvest time for each treatment. Fresh stems, leaves, and fruits of tomato were collected and placed into different paper bags. After weighing the fresh weight, the samples were placed into an oven at 100 °C for 20 min and then dried at 70 °C until the weight remained constant. Their dry matter weights were then determined.

Ten uniform and disease-free young tomato fruits with the same pollination date and similar size were marked at each plot. About 50 days after pollination, tomato fruits began to be harvested. After every harvest, each tomato was weighed to determine the mean fruit weight. Yield per hectare was then obtained by multiplying the mean fruit weight by fruit number per square.

In the first harvest, three representative tomato fruits among the marked fruits in each treatment were selected for analysis of fruit quality. The fruit flesh samples were liquified in a blender, and the liquid extract was immediately used to measure the total soluble solids, Vc, Lycopene, organic acid, and soluble protein (%).

Total soluble solids were determined with a hand-held instrument (BX-1, KEM, TKY, Japan). Vc and soluble protein were determined using the method of Li. H.S. [29]. Lycopene and organic acid were measured spectrophotometrically [30].

2.4.3. ET_a, WUE, and NUE

Evapotranspiration was estimated using the water balance formula [31]. The formula can be written as:

$$ET_a = I - D - R + K + P \pm \Delta \quad (2)$$

where ET_a is actual evapotranspiration during the whole growth period (mm); I is the amount of irrigation water during the whole growth period (mm); D is deep drainage (mm); R is surface run-off (mm); K is the contribution from the water table (mm); P is effective precipitation during the whole growth period; $\triangle$ is the change in the soil volumetric water content before transplanting and at the final harvest. No rainfall occurred inside the greenhouse. For drip irrigation under plastic mulch, surface run-off and deep percolation can be ignored since the amount of irrigation water was very little at a time. K was also neglected because the depth of the water table was over 25 m. Therefore, Equation (2) becomes:

$$ET_a = I \pm \Delta \quad (3)$$

In order to determine actual ET_a, the change in soil water content to 100 cm depth was measured prior to transplanting and at the final harvest. The soil volumetric water content between 0 cm to 100 cm depth was determined at 20 cm depth increments using Time Domain Reflectometry (TDR) (Trime-FM, IMKO, Berlin, Germany).

$$\Delta = 1000 \times H \times (\theta_1 - \theta_2) \quad (4)$$

where H is the depth of the soil wetting layer, θ_1 is the mean soil volumetric water content before transplanting, and θ_2 is the mean soil volumetric water content after harvest.

WUE was determined with Equation (5) as follows [32]:

$$WUE = \frac{Y}{ET_a} \quad (5)$$

where *WUE* is water use efficiency; Y is total fruit yield (kg ha^{-1}).

Nitrogen use efficiency was determined as follows:

$$NUE = \frac{Y}{N} \quad (6)$$

where N is applied fertilizer (kg ha^{-1}).

2.5. Statistical Analysis

Analysis of variance (ANOVA) was performed using the SPSS software package (SPSS V18.0, IBM, SU, USA). All data were the mean of replicates per treatment. All treatment means were compared using the least significant differences (LSD) at a 5% significance level. ANOVAs were conducted using nitrogen application and irrigation water amount as the primary factors.

3. Results

3.1. Net Photosynthetic Rate

Figure 2 shows that nitrogen and irrigation significantly affected the net photosynthetic rate of tomato leaves. Under the same nitrogen application levels, the highest value of leaf net photosynthetic rate of W_2 was obtained, which increased by 7.7% and 39.3% compared with that of W_3 and W_1. Under the same irrigation levels, such a trend of $N_3 > N_4 > N_2 > N_1$ was observed. Under medium water (W_2) and high water (W_3), N_3 and N_4 showed no significant difference. Compared with N_4, N_2, and N_1, the net photosynthetic rate of leaves at N_3 treatment increased by 2.4%, 15.4%, and 29.3% on average. The results showed that both irrigation and nitrogen could increase the net photosynthetic rate of tomato leaves. However, too much irrigation and nitrogen application inhibited crops' photosynthesis, thus affecting biomass accumulation.

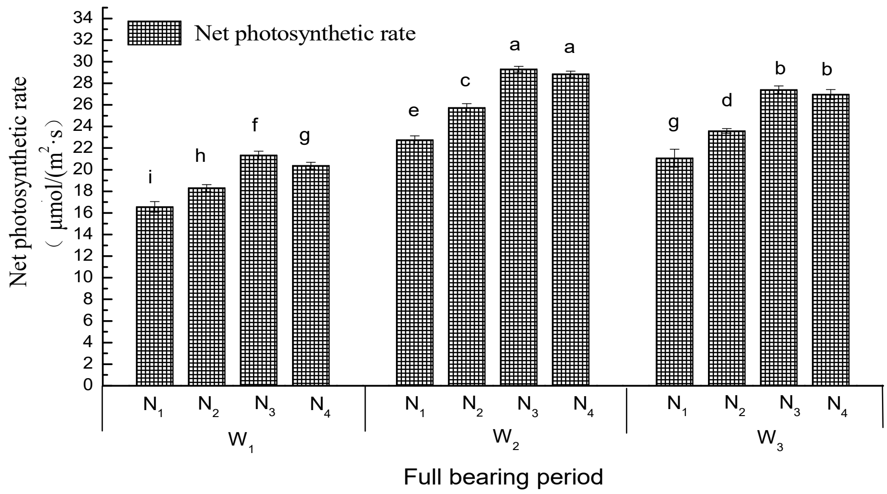

Figure 2. Effects of different water and nitrogen treatments on the net photosynthetic rate at full fruit-bearing stage. Note: if there are the same lowercase letters on the bars, this indicates that there is no significant difference among treatments at the 0.05 level. W_1, 0.75 actual evapotranspiration (ET_c); W_2, 1.00 ET_c; W_3, 1.25 ET_c. N_1 (120 N hm^{-2}), N_2 (220 N hm^{-2}), N_3 (320 kg N hm^{-2}), N_4 (420 kg N hm^{-2}).

3.2. Dry Biomass Cumulative

Table 3 shows that the dry biomass of different tomato organs varied widely under different water and nitrogen supplies. The results showed that increasing the application amount of water and nitrogen in the range of (0.75–1.0) ET_c and (120–320) kg ha^{-1} was beneficial to the growth of the tomato. There was no significant difference in root dry biomass under different nitrogen application rates at W_1. Under the same nitrogen application level, the root dry biomass of W_2 was higher than W_3 and W_1. The dry stem biomass increased gradually when the nitrogen application rate increased from N_1 to N_3 at W_1. When nitrogen fertilizer continued to increase to N_4, dry stem biomass decreased, but there was no significant difference between N_3 and N_4.

Table 3. Effects of different water and nitrogen supplies on dry matter accumulation and distribution of greenhouse tomatoes.

Irrigation Amount	Nitrogen Application Rate	Dry Biomass Cumulative (g/Plant)				
		Root	Stem	Leaf	Fruit	Total
W_1 (0.75 ET_c)	N_1	9.19 f	82.06 g	88.89 f	89.39 i	269.53 i
	N_2	9.55 f	92.48 f	99.29 e	96.97 hi	298.29 h
	N_3	9.69 f	100.34 e	114.51 d	109.04 fg	333.59 f
	N_4	9.34 f	97.81 e	104.70 e	106.77 g	318.62 g
W_2 (1.0 ET_c)	N_1	12.37 d	96.74 of	115.00 d	137.98 c	362.09 e
	N_2	13.72 bc	118.51 c	119.74 d	147.93 b	399.90 c
	N_3	15.39 a	130.95 b	129.18 bc	157.04 a	432.57 a
	N_4	14.39 b	122.68 c	121.07 cd	153.04 ab	411.18 bc
W_3 (1.25 ET_c)	N_1	11.34 e	111.37 d	128.74 bc	98.72 h	350.17 e
	N_2	12.54 d	122.95 c	134.51 ab	114.96 of	384.98 d
	N_3	13.58 c	139.28 a	140.07 a	124.23 d	417.17 b
	N_4	12.26 d	130.38 b	139.30 a	118.21 de	400.15 c

Note: The data are the averages of 3 replicates. Different lowcase letters in the same column indicate significant differences among treatments at 0.05 levels. The same lowcase letters in the same column show that difference is not significant. The same as below.

Regarding leaf analysis, there was no significant difference in N_3 and N_4 under medium and high water treatments. In terms of fruit analysis, there was no significant difference between N_3 and N_4 treatments under different water treatment conditions, and

$N_4 < N_3$. The maximum dry biomass of fruit under W_2N_3 treatment reached 157.04 g. Compared with W_1, the total dry biomass weight of W_2 and W_3 treatment increased by 31.6% and 27.3%, respectively. Compared with the N_1 treatment, the total dry biomass weight of N_2, N_3, and N_4 treatment increased by 10.3%, 20.5%, and 15.1%, respectively. The results showed that the plant could obtain the maximum dry biomass weight under water supply (W_2) conditions and recommended fertilizer amount (N_3).

3.3. Yield, WUE, NUE

As shown in Table 4, the fruit yield of the tomato varied widely at different treatments. The fruit yield ranged from 53.21 t ha^{-1} to 93.47 t ha^{-1}. The highest yields were found at N_3 levels, with an average of 77.44 t ha^{-1}. The maximum tomato yield was reached at irrigation levels of 100% ET_c. If the irrigation water continues to increase, tomato production will decrease.

Table 4. Effects of different water and nitrogen levels on yield, *WUE*, *NUE* of greenhouse tomatoes.

Irrigation Amount	Nitrogen Application Rate	Yield (t ha^{-1})	*WUE* (kg m^{-3})	*NUE* (kg kg^{-1} N)
W_1 (0.75 ET_c)	N_1	53.21 i	23.1 f	443.4 c
	N_2	57.72 hi	25.1 e	262.4 f
	N_3	64.91 fg	28.2 bcd	202.8 h
	N_4	63.55 g	27.6 cd	151.3 i
W_2 (1.0 ET_c)	N_1	82.13 c	26.8 d	684.4 a
	N_2	88.05 b	28.7 bc	400.2 d
	N_3	93.47 a	30.5 a	292.1 e
	N_4	91.09 ab	29.7 ab	216.9 gh
W_3 (1.25 ET_c)	N_1	58.76 h	15.3 h	489.7 b
	N_2	68.43 of	17.8 g	311.0 e
	N_3	73.95 d	19.3 g	231.1 g
	N_4	70.36 de	18.3 g	167.5 i

It is well known that an increase in nitrogen fertilizer can improve yield, but when nitrogen exceeds a threshold, it can have a negative effect. In our case, a yield increase (19.7%) was obtained by increasing nitrogen from 120 to 320 kg N ha^{-1}, then the yield decreased by 3.3% at 420 kg ha^{-1}. The results show that the optimum nitrogen rate was close to 320 kg N ha^{-1}.

WUE and *NUE* in different treatments are presented in Table 4. The *WUE* was increased by improving N application, but it decreased when the nitrogen rates reached 420 kg ha^{-1}. The highest *WUE* was observed in the W_2N_3 treatment. The value was 30.5 kg m^{-3}.

The *NUE* increased with decreasing N rates at the same irrigation conditions. Moreover, the *NUE* significantly increased with increasing irrigation water amount reasonably at the same nitrogen level, but excessive irrigation decreased nitrogen use efficiency. The highest *NUE* was obtained in the W_2N_3 treatment.

3.4. Tomato Quality

It can be seen from Table 5 that different quality parameters (vitamin C, lycopene, organic acid, and soluble protein) of the tomato were consistent under different water and nitrogen treatments. Under the same nitrogen application level, the trend was firstly increased and then decreased with the increase in irrigation amount. Under the same irrigation level, with the increase in nitrogen application rate, the trend of first increasing and then decreasing also appeared. Taking lycopene as an example, under the same irrigation amount, the lycopene content under N_3 treatment was higher than that of N_1, N_2, and N_4, with an average increase of 11.3%, 5.5%, and 5.0%, respectively, indicating that rational nitrogen application can increase the content of lycopene. In contrast, insufficient or excessive nitrogen application was not conducive to the formation of lycopene. Under the same nitrogen application rate, lycopene under W_2 treatment was higher than that under W_1 and W_3 treatment, with an average increase of 30.8% and 9.2%, respectively. The results showed that medium water treatment (W_2) was beneficial to the synthesis of lycopene, but insufficient or excessive water irrigation was not conducive to the formation of lycopene.

Table 5. Effects of different irrigation and nitrogen levels on fruit concentrations of vitamin C (Vc), lycopene, total soluble solids (TSS), organic acid and soluble protein.

Irrigation Amount	Nitrogen Application Rate	Vc (mg kg^{-1})	Lycopene (mg kg^{-1})	Soluble Solids (%)	Organic Acid (%)	Soluble Protein (%)
W_1 (0.75 ET_c)	N_1	13.97 g	22.30 h	4.77 e	0.41 g	15.33 e
	N_2	14.07 fg	23.84 gh	4.87 de	0.47 def	16.20 de
	N_3	14.91 f	24.93 fg	5.55 c	0.52 bc	18.53 abcd
	N_4	14.51 fg	23.42 gh	4.96 de	0.47 def	17.10 cde
W_2 (1.0 ET_c)	N_1	17.15 cd	29.01 bcde	5.45 c	0.45 ef	17.90 abcde
	N_2	18.07 ab	30.77 abc	6.16 b	0.53 bc	18.06 abcd
	N_3	18.80 a	32.57 a	7.0 a	0.62 a	20.13 a
	N_4	17.76 bc	31.20 ab	6.06 b	0.56 b	18.99 abc
W_3 (1.25 ET_c)	N_1	16.07 e	27.03 of	5.11 d	0.44 f	17.42 bcde
	N_2	16.30 de	28.05 de	5.63 c	0.50 cd	18.37 abcd
	N_3	17.02 cd	29.66 bcd	6.33 b	0.55 b	20.49 a
	N_4	16.38 de	28.42 cde	5.57 c	0.48 de	19.90 ab

4. Discussion

4.1. Pn

Water and nitrogen are the main factors affecting the net photosynthetic rate (Pn) [33]. The Pn under medium water (W_2) treatment was the highest. It was not conducive to crop growth under deficient irrigation (W_1) or excessive irrigation (W_3), which would inhibit root growth and thus affect the formation of photosynthetic products. The Pn under the N_3 treatment was significantly higher than the N_1 and the N_2. However, Pn decreased under the N_4 treatment because appropriate nitrogen application can improve the chloroplast on photosynthetic carbon assimilation enzyme activity [34]. When the nitrogen dose is too high (N_4), excessive nitrogen fertilizer will inhibit the growth of crops, and the leaf net photosynthetic rate no longer increases. At the same time, it also leads to feedback suppression of photosynthetic organs, resulting in a lower net photosynthetic rate of the leaves [35].

4.2. Dry Biomass

There is a high correlation between crop yield and dry biomass accumulation, which could be promoted by optimizing water and nitrogen input. Li et al. [36] found that the dry biomass of the tomato during the whole growth period was about 256–361 g. It was found that a certain range of irrigation and fertilizer had significant effects on the dry biomass of the tomato, mainly because water and nitrogen could change the growth environment of the root system. Insufficient or excessive water and nitrogen supply would affect the root system's absorption and utilization of water and nutrients and then affect the accumulation of aboveground biomass and the formation of yield.

4.3. Yield, WUE, and NUE

Rational irrigation and fertilization are effective ways to utilize water and fertilizer efficiently. Some researchers believed that the yields of tomato [37], muskmelon [38], and cotton [39] increased with an increase in water and fertilizer application. However, excessive or insufficient irrigation and fertilization are not conducive to yield formation. The results of this experiment showed that under the same nitrogen application level, the yield of the tomato under medium water treatment was the highest, indicating that insufficient irrigation and excessive irrigation would lead to yield reduction. Too much irrigation water will aerate the soil poorly and affects root respiration, which leads to lower yield. Under the same irrigation condition, the yield of N_3 treatment was the highest. Insufficient nitrogen application made the plant unable to obtain enough nitrogen, resulting in poor growth and development. However, too much nitrogen will lead to excess nitrogen in the soil, which will result in secondary salinization of the soil and eventually lower yields. Studies have shown that crop yield presents a quadratic parabola trend with the increase in nitrogen and nitrogen application amount [40,41], and tomato yield increases with the increase in water and nitrogen application amount. However, above a certain threshold value, the yield will decrease. Appropriate water and nitrogen supply can promote an increased yield.

Ertek et al. [42] believed that water use efficiency is high under deficient irrigation, and high irrigation amount often leads to the low production efficiency of irrigation water. This study found that the utilization efficiency of irrigation water was not high due to excessive irrigation or insufficient irrigation amount, which may cause the obvious decline in yield.

The *NUE* varied widely at different nitrogen levels, and it ranged from 151.3 kg kg^{-1}N to 684.4 kg kg^{-1}N. The most efficient treatment was the one with less nitrogen. That is because of the fact that crops assimilate mineral nitrogen from the soils in the lower nitrogen treatments. On the contrary, when the nitrogen rate is excessive, it will restrict plant growth. Erdem et al. [43] found that *WUE* decreased with the increase in irrigation amount, and nitrogen partial productivity decreased with the increase in nitrogen.

4.4. Quality

The quality of the tomato is an important parameter in evaluating its nutritional rate, and water and nitrogen are the main factors affecting tomato quality. Some studies have shown that crop quality is closely related to the irrigation level [44]. The content of soluble sugar, vitamin C and lycopene in the flesh could be increased by proper water stress. In this experiment, however, it was found that, compared with medium water treatment, tomato quality indexes were reduced under low irrigation conditions, indicating that water stress was not conducive to the formation of tomato nutritional quality. Water deficit reduces root activity, accelerates root senescence, and reduces yield and fruit quality. Xing et al. [37] reported similar results. With the increase in irrigation amount, the quality index of the tomato first increased and then decreased, indicating that proper irrigation can improve the quality of tomatoes. However, when the irrigation amount continues to increase, excess water will dilute the quality, thus reducing the content of each quality parameter. Nitrogen application research shows that the quality of the tomato is related to the nitrogen application rate. The soluble sugar and vitamin C in pulp increased with the increase in nitrogen. However, the soluble sugar and vitamin C content will reduce if the nitrogen application rate is above the critical value. Excessive nitrogen can inhibit phosphorus absorption and potassium elements, which can cause poor quality.

5. Conclusions

This study found that the net photosynthetic rate of tomato leaves increased and then decreased with the increase in irrigation and nitrogen application. The net photosynthetic rate of tomato leaves reached the maximum under W_2N_3 treatment. Appropriate irrigation and nitrogen application significantly increased the biomass of tomato plants, while excessive irrigation and nitrogen application had negative effects on biomass accumulation. Reasonable water and nitrogen supply could provide a good water and fertilizer environment for the root system, improve the net photosynthetic rate of tomato leaves, and provide the foundation for high yield.

The irrigation level of 1.0 ET_c and nitrogen level of 320 N ha^{-1} was recommended as the optimal water and nitrogen management for tomato growth in our conditions, which can improve the yield, quality, *WUE*, *NUE* of tomatoes under drip irrigation with plastic film mulch. As we know, tomatoes can achieve the best quality under moderate water deficit conditions, so more irrigation levels should be explored to determine the optimal irrigation water amount based on the best quality.

Author Contributions: Conceptualization, W.Y. and L.L.; methodology, Y.B. and N.L.; investigation, S.C.; writing—original draft preparation, W.Y.; writing—review and editing, N.L. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the key Laboratory for Technology in Rural Water Management of Zhejiang Province (JWEU-RWM-202103), the Basic Public Welfare Technology Research Program of Zhejiang province (LGN19E090001) and the National Natural Science Foundation of China (52109069).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data that support the finding of this study are available from the author upon reasonable request.

Acknowledgments: We sincerely thank the China Scholarship Council (CSC) for the financial support of Wenjun Yue (201908330267) for his visiting research.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Teklay, T.; Abadi, B.; Mebrahtu, G. Optimizing Irrigation Water and Nitrogen Fertilizer Levels for Tomato Production. *Open Agric. J.* **2019**, *13*, 198–206.
2. Arah, I.K.; Amaglo, H.; Kumah, E.K.; Ofori, H. Preharvest and postharvest factors affecting the quality and shelf life of harvested tomatoes. A mini review. *Int. J. Agron.* **2015**, *2015*, 478041. [CrossRef]
3. De-Pascale, S.; Maggio, A.; Fogliano, V.; Ambrosino, P.; Ritieni, A. Irrigation with saline water improves carotenoids content and antioxidant activity of tomato. *J. Hortic. Sci. Biotechnol.* **2001**, *76*, 447–453. [CrossRef]
4. Evgenidis, G.; Traka-Mavrona, E.; Koutsika-Sotiriou, M. Principal component and cluster analysis as a tool in the assessment of tomato hybrids and cultivars. *Int. J. Agron.* **2011**, *2011*, 697879. [CrossRef]
5. Farre, G.; Sanahuja, G.; Naqvi, S.; Bai, C.; Capell, T.; Zhu, C.; Christou, P. Travel advice on the road' to carotenoids in plants. *Plant Sci.* **2010**, *179*, 28–48. [CrossRef]
6. Zhao, H.; Xiong, Y.C.; Li, F.M. Plastic film mulch for half growing-season maximized WUE and yield of potato via moisture-temperature improvement in a semi-arid agroecosystem. *Agric. Water Manag.* **2012**, *104*, 68–78. [CrossRef]
7. Rodriguez, J.C.; Shaw, N.L.; Cantliffe, D.J. Influence of plant density on yield and fruit quality of greenhouse-grown Galia muskmelons. *HortTechnology* **2007**, *17*, 580–585. [CrossRef]
8. Zhu, J.H.; Li, J.L.; Li, X.L.; Zhang, F.S. Effects of compound fertilizers utilized on soil environmental quality in protected vegetable field. *Agro-Environ. Protect.* **2002**, *21*, 5–8. (In Chinese with English abstract)
9. Yuan, B.Z.; Kang, Y.; Nishiyama, S. Drip irrigation scheduling for tomatoes in unheated greenhouses. *Irrig. Sci.* **2001**, *20*, 149–154. [CrossRef]
10. Hassanien, R.H.E.; Li, M.; Lin, W.D. Advanced applications of solar energy in agricultural greenhouses. *Renew. Sustain. Energy Rev.* **2016**, *54*, 989–1001. [CrossRef]
11. Fan, J.; Chen, B.; Wu, L.; Zhang, F.; Lu, X.; Xiang, Y. Evaluation and development of temperature-based empirical models for estimating daily global solar radiation in humid regions. *Energy Convers. Manag.* **2018**, *144*, 903–914. [CrossRef]
12. Fan, J.; Wang, X.; Wu, L.; Zhang, F.; Bai, H.; Lu, X.; Xiang, Y. New combined models for estimating daily global solar radiation based on sunshine duration in humid regions: A case study in South China. *Energy Convers. Manag.* **2018**, *156*, 618–625. [CrossRef]
13. Kiymaz, S.; Ertek, A. Yield and quality of sugar beet (*Beta vulgaris* L.) at different water and nitrogen levels under the climatic conditions of Kirsehir, Turkey. *Agric. Water Manag.* **2015**, *158*, 156–165. [CrossRef]
14. Yue, W.; Chen, X.; Wang, W.; Zhang, F. Effects of different nitrogen treatments on yield and quality of greenhouse muskmelon under mulched drip irrigation condition. *J. Plant Nutr. Fertil.* **2019**, *25*, 461–469, (In Chinese with English abstract).
15. Kuscu, H.; Turhan, A.; Ozmen, N.; Aydinol, P.; Demir, A.O. Optimizing levels of water and nitrogen applied through drip irrigation for yield, quality, and water productivity of processing tomato (*Lycopersicon esculentum* Mill.). *Hortic. Environ. Biotechnol.* **2014**, *55*, 103–114. [CrossRef]
16. Mitchell, J.P.; Shennan, C.; Grattan, S.R.; May, D.M. Tomato fruit yields and quality under water stress and salinity. *J. Am. Soc. Hortic. Sci.* **1991**, *116*, 215–221. [CrossRef]

17. Kirda, C.; Cetin, M.; Dasgan, Y.; Topcu, S.; Kaman, H.; Ekici, B.; Derici, M.; Ozguven, A. Yield response of greenhouse-grown tomato to partial root drying and conventional deficit irrigation. *Agric. Water Manag.* **2004**, *69*, 191–201. [CrossRef]
18. Wang, X.; Xing, Y. Evaluation of the effects of irrigation and fertilization on tomato fruit yield and quality: A principal component analysis. *Sci. Rep.* **2017**, *7*, 350. [CrossRef]
19. Ju, X.T.; Kou, C.L.; Christie, P.; Dou, Z.X.; Zhang, F.S. Changes in the soil environment from excessive application of fertilizers and manures to two contrasting intensive cropping systems on the North China Plain. *Environ. Pollut.* **2007**, *145*, 497–506. [CrossRef]
20. Gutezeit, B. Yield and nitrogen balance of broccoli at different soil moisture levels. *Irrig. Sci.* **2004**, *23*, 21–27. [CrossRef]
21. Darwish, T.M.; Atallah, T.W.; Hajhassan, S.; Haidar, A. Nitrogen and water use efficiency of fertigated processing potato. *Agric. Water Manag.* **2006**, *85*, 95–104. [CrossRef]
22. Rajput, T.B.S.; Patel, N. Water and nitrate movement in drip-irrigated onion under fertigation and irrigation treatments. *Agric. Water Manag.* **2006**, *7*, 293–311. [CrossRef]
23. Bhat, R.; Sujatha, S.; Balasimha, D. Impact of drip fertigation on productivity of areca nut (*Areca catechu* L.). *Agric. Water Manag.* **2007**, *90*, 101–111. [CrossRef]
24. Wang, H.; Li, J.; Cheng, M.; Zhang, F.; Wang, X.; Fan, J.; Wu, L.; Fang, D.; Zou, H.; Xiang, Y. Optimal drip fertigation management improves yield, quality, water and nitrogen use efficiency of greenhouse cucumber. *Sci. Hortic.* **2019**, *243*, 357–366. [CrossRef]
25. Aujla, M.S.; Thind, H.S.; Buttar, G.S. Fruit yield and water use efficiency of eggplant (*Solanum melongena* L.) as influenced by different quantities of nitrogen and water applied through drip and furrow irrigation. *Sci. Hortic.* **2007**, *112*, 142–148. [CrossRef]
26. Kirnak, H.; Higgs, D.; Kaya, C.; Tas, I. Effects of irrigation and nitrogen rates on growth, yield, and quality of muskmelon in semiarid regions. *J. Plant Nutr.* **2005**, *28*, 621–638. [CrossRef]
27. Doorenbos, J.; Pruitt, W.O. *Guidelines for Predicting Crop Water Requirements. Irrigation and Drainage Paper No. 24*; Food and Agriculture Organization: Roma, Italy, 1977.
28. Chen, X.; Cai, H.; Li, H.; Wang, J.; Du, W. Calculation of crop evapotranspiration in greenhouse. *Chin. J. Appl. Ecol.* **2007**, *18*, 317–321. (In Chinese)
29. Li, H.; Sun, Q.; Zhao, S.; Zhang, W. *Principles and Techniques of Plant Physiological Biochemical Experiment*; Higher Education Press: Beijing, China, 2000; pp. 182–248. (In Chinese)
30. Garcia-Bobledo, E.; Corzo, A.; Papaspyrou, S. A fast and direct spectrophotometric method for the sequential determination of nitrate and nitrite at low concentrations in small volumes. *Mar. Chem.* **2014**, *162*, 30–36. [CrossRef]
31. Andreu, L.; Hopmans, J.; Schwankl, L. Spatial and temporal distribution of soil water balance for a drip-irrigated almond tree. *Agric. Water Manag.* **1997**, *35*, 123–146. [CrossRef]
32. Ertek, A.; Sensoy, S.; Gedik, I.; Küçükyumuk, C. Irrigation scheduling based on pan evaporation values for cucumber (*Cucumis sativus* L.) grown under field conditions. *Agric. Water Manag.* **2006**, *81*, 159–164. [CrossRef]
33. Mofokeng, M.; Steyn, J.; Du-Plooy, C.; Prinsloo, G.; Araya, H. Growth of pelargonium sidoides DC. in response to water and nitrogen level. *S. Afr. J. Bot.* **2015**, *100*, 183–189. [CrossRef]
34. Xu, L.; Huang, S.; Tao, H.; Wang, Y.; Qi, L.; Wang, P. Effects of Different Nitrogen Regimes on Canopy Structure and Partial Physiological and Agronomic Traits in Summer Maize. *Acta Agron. Sin.* **2012**, *38*, 301–306. (In Chinese with English abstract) [CrossRef]
35. Du, Y.; Cao, H.; Liu, S.; Gu, X.; Cao, Y. Response of yield, quality, water and nitrogen use efficiency of tomato to different levels of water and nitrogen under drip irrigation in Northwestern China. *J. Integr. Agric.* **2017**, *16*, 1153–1161. [CrossRef]
36. Li, J.; Zhang, F.; Fang, D.; Li, Z.; Gao, M.; Wang, H.; Wu, D. Effects of water and nitrogen supply on the growth and water use efficiency of cucumber (*Cucumis sativus* L.) under fertigation. *Sci. Agric. Sin.* **2014**, *47*, 4475–4487. (In Chinese with English abstract)
37. Xing, Y.; Zhang, F.; Wu, L.; Fan, J.; Zhang, Y.; Li, J. Determination of optimal amount of irrigation and fertilizer under drip fertigated system based on tomato yield, quality, water and fertilizer use efficiency. *Trans. Chin. Soc. Agric. Eng.* **2015**, *31* (Suppl. S1), 110–121. (In Chinese with English abstract)
38. Yue, W.; Zhang, F.; Li, Z.; Zou, H.; Gao, Y. Effects of water and nitrogen coupling on nitrogen uptake of muskmelon and nitrate accumulation in soil. *Trans. Chin. Soc. Agric. Mach.* **2015**, *46*, 88–96. (In Chinese with English abstract)
39. Wu, L.; Zhang, F.; Zhou, H.; Suo, Y.; Xue, F.; Zhou, J.; Liang, F. Effect of drip irrigation and fertilizer application on water use efficiency and cotton yield in North of Xinjiang. *Trans. Chin. Soc. Agric. Eng.* **2014**, *30*, 137–146. (In Chinese with English abstract)
40. Song, N.; Wang, F.; Yang, C.; Yang, K. Coupling effects of water and nitrogen on yield, quality and water use of potato with drip irrigation under plastic film mulch. *Trans. Chin. Soc. Agric. Eng.* **2013**, *29*, 98–105. (In Chinese with English abstract)
41. Chai, Z.; Wang, X.; Sun, X.; Jiang, A.; Bai, R. Influence on growth and yield of zizyphus jujube under coupling of water and nitrogen. *Res. Soil Water Conserv.* **2012**, *19*, 201–204+209. (In Chinese)
42. Ertek, A.; Sensoy, S.; Küçükyumuk, C.; Gedik, I. Irrigation frequency and amount affect yield components of summer squash (*Cucurbita pepo* L.). *Agric. Water Manag.* **2004**, *67*, 63–76. [CrossRef]
43. Erdem, T.; Arin, L.; Erdem, Y.; Polat, S.; Deveci, M.; Okursoy, H.; Gültaş, H.T. Yield and quality response of drip irrigated broccoli (*Brassica oleracea* L. var. italica) under different irrigation regimes, nitrogen applications and cultivation periods. *Agric. Water Manag.* **2010**, *97*, 681–688. [CrossRef]
44. Gupta, A.; Chattoo, M.; Singh, L. Drip irrigation and fertigation technology for improved yield, quality, water and fertilizer use efficiency in hybrid tomato. *J. AgriSearch* **2015**, *2*, 94–99.