Development of an Automatic Irrigation Method Using an Image-Based Irrigation System for High-Quality Tomato Production

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Abstract: In this study, we developed an automatic irrigation method using an image-based irrigation system for high-quality tomato production in a greenhouse by investigating effects of a diurnal periodic cycle of irrigation on the photosynthesis, growth, yield, and fruit quality of tomatoes. The diurnal periodic cycle in a moderate wilting–full recovery treatment (MR) with a medium threshold value was more frequent than that in a severe wilting–full recovery treatment (SR) with a high threshold value. Mean daily maximum wilting ratios for MR and SR were 7.2% and 11.3%, respectively, when wilting ratios were set to threshold values of 7% and 14%, respectively. Total irrigation amounts in MR and SR were similar and lower than that in the untreated control. Net photosynthetic rate decreased under water stress, with values in MR being higher than that in SR, and recovered rapidly to more than 90% of its maximum value following irrigation. Plant growth and fruit yield per plant in MR and SR were lower than that in the control. Water stress treatment could improve fruit quality when it commenced at the anthesis stage or early fruit development stage. Total irrigation amount was a more important parameter than the threshold value for controlling the growth, yield, and fruit quality of tomatoes.

Keywords: Brix; greenhouse; net photosynthetic rate; water stress; wilting level

1. Introduction

Compared with standard cultivated tomatoes in a greenhouse, high-quality tomatoes have higher Brix and acidity values [1,2], and the demand for these superior fruits is growing concomitant with ongoing increase in living standards. Numerous studies have indicated that although water stress treatment can be used to produce high-quality tomatoes [3–5], such stress inhibits photosynthesis [6–8], thereby reducing the growth, fruit weight, and yield of tomatoes [9–11].

In commercial greenhouse tomato production, growers routinely spend a significant amount of time monitoring tomato plants throughout the cultivation period for signs of wilting to avert excessive wilting or associated physiological disorders. The monitoring of wilting and appropriate irrigation management are important measures for controlling the growth, yield, and fruit quality of tomatoes. Recent studies have reported that wilting conditions in tomato plants can be digitized based on real-time monitoring of factors such as stem diameter [12], leaf temperatures using infrared thermometry [13], plant weight [14], projected leaf area using photo-image analysis [15] and artificial intelligence [16,17], for high-quality tomato production. Notably, in a number of these studies, researchers have monitored diurnal periodic cycles of wilting–recovery and irrigated when wilting conditions reached a certain threshold value. However, few of these studies have sought to investigate the optimal irrigation amount per time and the set point of the threshold value for starting irrigation (hereafter, referred as ‘threshold value’) as the wilting level.
Several studies without real-time plant monitoring have examined responses of greenhouse tomatoes to water stress induced by irrigation management, including effects of irrigation frequency per day or week [4,18] and total irrigation amounts [2] based on controlling the soil water content, transpiration estimation, or irrigation scheduling. However, as these methods for wilting and recovery often take time, some of these studies reported that the period of water stress and recovery in tomatoes was a few days or weeks [2]. With respect to the effect of irrigation frequency on tomatoes, it has been demonstrated that increasing irrigation frequency during daytime while maintaining the same total irrigation amount per day promoted an increase in the net photosynthetic rate [19] (p. 403), as well as an increase in the number of fruits and tomato yield [20]. In contrast, Harmanto et al. [21] reported no effect of increasing irrigation frequency on tomato yield under the same total irrigation amount per day. However, given that these studies did not consider the wilting levels at irrigation and their transition throughout the experiments, it is difficult to determine the factors contributing to these disparate observations.

In order to optimize irrigation management using an automatic irrigation system for high-quality tomato production in a greenhouse, Hikosaka et al. [1] developed an image-based irrigation system that enables the monitoring of wilting conditions at 1 min intervals using photo-images of greenhouse tomatoes. This irrigation system can control (1) the threshold value as a wilting level for irrigation and (2) the irrigation amount per time, which leads to full or partial recovery of plants after irrigation. However, a proper irrigation method with a combination of (1) and (2) has not been investigated for this irrigation system. It is possible that the diurnal periodic cycle of wilting and recovery at different levels affects the net photosynthetic rate, growth, yield, and fruit quality of tomatoes.

In addition, to produce high-quality tomatoes using an automatic irrigation system, it is necessary to elucidate the optimal fruit stage at which water stress treatment should commence under a periodic cycle of controlled wilting and recovery during the treatment period. In this regard, the quality of tomato fruits improving when water stress treatment commences at the anthesis stage [3] or at the stages of fruit development [10] or fruit ripening [22] is debated.

Therefore, the objective of the present study was to develop an automatic irrigation method for a diurnal periodic cycle of wilting–full recovery using the image-based irrigation system for high-quality tomato production in a greenhouse and to determine the optimal fruit stage for commencing water stress treatment. To this end, we investigated the effects of a diurnal periodic cycle of irrigation with two combinations of wilting level and full recovery on the photosynthesis, growth, yield, and fruit quality of tomatoes.

2. Materials and Methods

2.1. Experimental Site and Plant Materials

The experiment was conducted in a greenhouse (cultivation area of 144 m²) on the Matsudo campus of Chiba University, Japan (35°46′ N, 139°54′ E). The roof and sides of the greenhouse were covered with a fluorine-based film and a polyolefin film, respectively. The greenhouse was equipped with automatic roof and side-wall ventilators with 0.4 mm anti-insect screens. The ventilation windows, shading curtains, and heating system in the greenhouse were controlled by a ubiquitous environment control system (WaBit Inc., Fukuoka, Japan). The nighttime minimum air temperature was set to 15 °C.

We used tomato plants (Solanum lycopersicum L., ‘Furutika’; Takii & Co., Ltd., Kyoto, Japan). Tomato seeds were sown on 13 August 2020, and seedlings were cultivated using a closed plant production system under the following conditions: air temperature of 25/20 °C (daytime/nighttime), relative humidity of 70%, light period of 16 h d⁻¹, and CO₂ concentration of 1000 μmol mol⁻¹. The seedlings were irrigated with water for 7 days after sowing (DAS) and then irrigated with a nutrient solution (half unit of Otsuka-A nutrient solution; OAT Agrio Co., Ltd., Tokyo, Japan). The nutrient solution (one-unit) had the following content (mol m⁻³): NO₃⁻ 16, H₂PO₄⁻ 3⁻ 4, Ca²⁺ 4, Mg²⁺ 2, K⁺ 8, and NH₄⁺ 1.3,
and some micronutrients. The electrical conductivity (EC) and pH of the nutrient solutions were 2.7 dS m$^{-1}$ and 6.8, respectively.

At 35 DAS, seedlings were transplanted to plastic pots (1.6 L), filled with coconut fiber substrate (coco wool; Hoags Inc., Tokyo, Japan), and placed on cultivation beds in the greenhouse. Pots containing a single seedling were arranged in a straight line spaced 25 cm apart. Seedlings were irrigated with one unit of the aforementioned nutrient solution (1.08 L d$^{-1}$ per plant) by drip irrigation (Netafim Ltd., Tel Aviv, Israel). During the experiment, we removed axillary buds and old leaves, and sprayed plants with a pesticide and commercial hormonal solution (Tomato Tone; ISK Biosciences K.K., Tokyo, Japan). Tomato plants were also sprayed weekly with 1% CaCl$_2$ to inhibit the occurrence of blossom end rot.

2.2. Treatments

The experiment included a single sufficient irrigation treatment as a control and two water stress treatments, namely, a moderate wilting–full recovery treatment (MR) and a severe wilting–full recovery treatment (SR), with 12 tomato plants in each treatment. In the control treatment, timed irrigation was applied to provide a sufficient nutrient solution of 1.08 L d$^{-1}$ per plant from 06:30 to 15:30.

The image-based irrigation system used in MR and SR monitored the wilting level of leaves in terms of wilting ratio ($W$ (%)) at 1 min intervals based on photo-images of the tomatoes and supplied a nutrient solution when $W$ reached a threshold value ($W_{\text{set}}$) [1]. $W$ was calculated based on the change in the projected leaf area of the canopy, as follows:

$$W(\%) = (1 - \text{PLA/PLA}_{\text{ref}}) \times 100$$  (1)

where PLA is the projected leaf area at a certain time and PLA$_{\text{ref}}$ is the reference-projected leaf area in the morning after sufficient irrigation.

In MR and SR, 50–60 mL of nutrient solution was applied from 07:00 to 08:30 to obtain the maximum PLA as PLA$_{\text{ref}}$; the exception being on cloudy or rainy days, when an excess accumulation of applied nutrient solution would be unlikely to cause wilting. When $W$ reached $W_{\text{set}}$ from 08:30 to 15:00, a single irrigation with nutrient solution was applied to promote the full recovery of plants from $W_{\text{set}}$, with the decision interval for irrigation based on $W$ being 5 min.

For the purposes of this study, $W_{\text{set}}$ in MR and SR was set to 7% and 14%, respectively, with corresponding single nutrient solution irrigation amounts of 40 and 120 mL per plant. In both treatments, $W$ recovered to between 0% and 2%. A $W_{\text{set}}$ value of 14% was established as the maximum $W$ for plant survival, at which all plant leaves were observed to be wilting. The water potential at this time was approximately −1.5 MPa (data not shown). At $W_{\text{set}}$ 7%, which was half the SR value, only the upper leaves wilted. Digital color images of tomato plants captured from the side at three wilting ratios (0%, 7%, and 14%) are shown in Figure 1. The maximum $W$ was confirmed based on observations undertaken prior to commencing the experiment, as $W$ determination can differ depending on the angle of the camera and the distance between the camera and the plant. In both treatments, 40–50 mL of nutrient solution was applied from 15:00 to 15:30 to prevent the plants from wilting before nighttime.
The daily light integral in the greenhouse was 10–17 mol m$^{-2}$d$^{-1}$ where $\Delta W(t)$ was almost constant when $W$ was in the range of 0–4% (data not shown). Therefore, we calculated the cumulative wilting ratio (CWR, % min$^{-1}$) using the sum of $W$ per minute higher than 4% during the 10 h from 07:00 to 17:00, as follows:

$$\text{CWR} = \sum_{t=1}^{n} \Delta W(t) \ (\Delta W(t) \geq 0) \quad (2)$$

where $\Delta W(t)$ is the difference between $W(t)$ and 4% at minute ‘t’, and ‘n’ is equal to 600. If $W(t) \leq 4\%$, $\Delta W(t) = 0$; otherwise, $\Delta W(t) = W(t) - 4\%$.

2.3.3. Plant Growth

Plant length was defined as the total length from the base to the top of the plant. Stem diameter was measured using a digital caliper at approximately 7 cm intervals for a total of 40 cm of the plant apex. Internode length was measured using a ruler, and total leaf area was determined using a leaf area meter (LI-3000C, LI-COR Inc., Lincoln, NE, USA). Fresh (FW) and dry (DW) weights of a whole plant, including leaves, stem, flowers, and fruit trusses, as well as removed axillary buds, old leaves, and harvested fruits, were measured using an electronic balance, with DW per plant being determined after drying plant material in a dry oven at 80 °C for 7 days. The dry matter ratio was calculated as $\text{DW} ÷ \text{FW}$. Measurements of these parameters were based on four plants randomly selected from those in each treatment at 83 days after commencing treatments (DAT).
2.3.4. Diurnal Change in Pn and Potential Values of Pn in Different Leaf Layers

Pn was measured using a portable photosynthesis measurement system (LI-6400XT, LI-COR Inc., Lincoln, NE, USA) equipped with a leaf cuvette mounted with an LED lamp (red:blue ratio = 9:1) under the following conditions: CO₂ concentration of 400 μmol mol⁻¹, air temperature of 25 °C, and PPFD of 800 μmol m⁻² s⁻¹.

Diurnal changes in Pn were measured on the sixth leaf from the apex, which was a newly expanding leaf sensitive to water stress, from 08:30 to 15:00. During the experimental period, three plants were randomly selected from each treatment to measure Pn when the RH was 35% ± 10%.

Plants were divided into upper, middle, and lower leaf layers, from each of which (comprising 7–8 leaves), we measured the potential value of Pn from 10:00 to 14:00 at 27, 29, 30, and 79 DAT. To prevent wilting during the measurement of potential Pn, plants were sufficiently irrigated from 08:30 to 14:00. In each treatment, six plants were randomly selected to measure the Pn in each layer, during which time the RH was 45% ± 10%.

2.3.5. Yield and Fruit Quality

Fruits were harvested eight times (20, 32, 46, 53, 59, 66, 73, and 79 DAT) throughout the experiment. Water stress treatment was commenced 62 days after transplantation, at which time the sixth fruit truss was at the anthesis stage. At the time of treatment commencement, the first harvested fruits (20 DAT) were at the ripening to mature stage, whereas the second to fourth harvested fruits (32, 46, and 53 DAT) were at the fruit development stage, and the fifth to eighth harvested fruits (59, 66, 73, and 79 DAT) were at the anthesis stage.

For each harvest, we recorded the number and weight of all fruits harvested from each truss, and six fruits were randomly selected from each truss to measure the Brix and acidity of tomatoes. Brix and acidity were measured non-destructively using a Brix and acidity analyzer (Fruit selector, K-BA100R; Kubota Corporation, Osaka, Japan). At the end of the experiment, the fruits were harvested up to the eighth fruit truss.

2.3.6. Cumulative Air Temperature of Fruit from Anthesis to Harvest

To estimate the anthesis date of fruits at each harvest, we used the cumulative air temperature (CAT), with values from sixth to eighth harvests in each treatment being recorded using 17–36 fruits borne on the fifth to eighth trusses. For both the control and MR treatments, the value of CAT was approximately 1080 °C, whereas it was somewhat lower for the SR treatment at 970 °C. We used CAT values to estimate the anthesis date of fruits from the sixth to eighth harvests and accordingly estimated the anthesis date of fruits from the first to fifth harvests, which were grown with sufficient irrigation and water stress, based on those of fruits from the sixth to eighth harvest. The anthesis and harvest dates of fruits obtained from the eight harvests in the control, MR, and SR treatments are shown in Figure 2. All plants in each treatment were sufficiently irrigated prior to commencing water stress treatment, with an irrigation amount of 1.08 L d⁻¹ per plant and a daily irrigation frequency of 36 times.

2.4. Statistical Analysis

With the exception of accumulated fruit yield, accumulated number of harvested fruits, and fruit weight, all data were analyzed with the IBM SPSS statistical software v24.0 (SPSS, Chicago, IL, USA) using a one-way analysis of variance (ANOVA). Significant differences among the control, MR, and SR were determined using the Tukey–Kramer’s test at \( p < 0.05 \).
3. Results

3.1. Irrigation Management

Typical diurnal changes in W for plants subjected to MR and SR, measured from 07:00 to 17:00 on sunny and cloudy days, are shown in Figure 3. Throughout the experiment, the cycles of wilting and recovery in the MR and SR treatments took 1 to 4 h, with plants recovering fully within an hour following irrigation. In MR, moderate wilting–recovery cycles were repeated three or four times on sunny days and once or twice on cloudy days, with a daily maximum W value of 7.1–7.5%, irrespective of weather conditions (data not shown). In contrast, we recorded a single cycle of wilting and recovery in SR, for which the interval between W\(_{\text{set}}\) and W at 0% was longer than that recorded for MR. Severe wilting–recovery cycles were detected once or twice on sunny days, whereas W failed to reach W\(_{\text{set}}\) on cloudy days. Consequently, on sunny and cloudy (or rainy) days, the maximum daily W for plants subjected to SR was 14.0–14.5% and 9.0–13.9%, respectively (data not shown). In both MR and SR, the values of W recovered to 0–2% following irrigation and before nighttime at 17:00. During the experimental period, 48 days were sunny (PPFD \(\geq 600 \mu\text{mol m}^{-2} \text{s}^{-1}\)) and 35 days were cloudy or rainy (PPFD < 600 \(\mu\text{mol m}^{-2} \text{s}^{-1}\)), and the mean daily maximum W in MR and SR was 7.2% and 11.3%, respectively.

Figure 2. The anthesis and harvest dates of eight fruit harvests in the control, moderate wilting–full recovery treatment (MR), and severe wilting–full recovery treatment (SR). DAT: days after commencing treatments.

Figure 3. Typical diurnal changes in the wilting ratio (W) in MR and SR from 07:00 to 17:00 on a sunny day (a) and a cloudy day (b). MR: moderate wilting–full recovery treatment; SR: severe wilting–full recovery treatment.
Moreover, the cumulative wilting ratio obtained for SR was 7–13 times higher than that for MR (Figure 4).

The total irrigation amounts in MR and SR were 34% and 40% of that in the control, respectively (Table 1). However, the total irrigation amount in SR was approximately 6 L higher than that in MR. This discrepancy can be attributed to system error in SR, which resulted in excess irrigations of 3 L on 60 and 61 DAT. Apart from these two dates, the MR and SR irrigation amounts were almost identical. The corresponding total irrigation frequencies in MR and SR were 6.0% and 2.5% of that in the control, with that in SR being approximately 44% of that in MR.

| Treatment | Total Irrigation Amount (L/plant) | Total Irrigation Frequency (Times) |
|-----------|----------------------------------|-----------------------------------|
| Control   | 89.6                             | 2988                              |
| MR \(^z\) | 30.7                             | 176                               |
| SR \(^y\) | 36.5                             | 77                                |

\(^z\): MR, moderate wilting–full recovery treatment; \(^y\): SR, severe wilting–full recovery treatment.

3.2. Photosynthesis

Under control condition, \(P_n\) values remained relatively constant throughout the day (Figure 5a), whereas in response to the diurnal cycle of water stress and recovery, \(P_n\) decreased to 75% and 60% of the maximum values on the same day, when \(W\) reached \(W_{set}\) under MR and SR conditions, respectively (Figure 5b,c). In both treatments, however, \(P_n\) recovered rapidly to more than 90% of its maximum value following irrigation.

Throughout the experiment, the potential values of \(P_n\) in the upper leaf layer were consistently higher than those recorded in the middle and lower leaf layers (Figure 6), which is indicative of the higher photosynthetic activity of the younger leaves borne at the upper nodes compared with mature leaves borne at the lower nodes. In the early period of monitoring (27, 29, and 30 DAT), we detected no significant differences among treatments with respect to \(P_n\) in the upper leaf layer (Figure 6a), whereas during the latter period (79 DAT), although we detected no significant difference between SR and control plants, \(P_n\) in the upper leaf layer of MR plants was found to be significantly lower than that in the control plants (Figure 6b). Moreover, throughout the experiment, \(P_n\) in the middle and lower leaf layers were negatively correlated with the levels of water stress, with \(P_n\) values being highest in the control plants and lowest in the SR plants.
3.2. Photosynthesis

Under control condition, Pn values remained relatively constant throughout the day (Figure 5a), whereas in response to the diurnal cycle of water stress and recovery, Pn decreased to 75% and 60% of the maximum values on the same day, when W reached W set (Figure 5). DAT: days after commencing treatments; MR: moderate wilting–full recovery treatment; SR: severe wilting–full recovery treatment.

![Figure 5](image)

**Figure 5.** Typical diurnal changes in the net photosynthetic rate (Pn) and wilting ratio (W) in the control (a), MR (b), and SR (c) from 08:30 to 15:00 on a sunny day. DAT: days after commencing treatments; MR: moderate wilting–full recovery treatment; SR: severe wilting–full recovery treatment.

3.3. Plant Growth

In the MR and SR plants, the recorded values of plant length, leaf area, internode length, FW, and DW were lower than the corresponding values obtained for control plants at 34 and 83 DAT. In contrast, the dry matter ratios of plants subjected to MR and SR were found to be higher than that of the control plants at 34 and 83 DAT, respectively (Table 2). However, we detected no significant difference between MR and SR plants at 34 and 83 DAT with respect to plant length, leaf area, internode length, FW, DW, and dry matter ratio.
Table 2. Effect of water stress on the growth of tomatoes recorded at 34 and 83 days after commencing treatment (DAT).

| DAT  | Treatment | Plant Length (m) | Leaf Area (m²/plant) | Internode Length (cm) | Fresh Weight (kg/plant) | Dry Weight (g/plant) | Dry Matter Ratio (%) |
|------|-----------|------------------|----------------------|------------------------|------------------------|----------------------|----------------------|
| 34   | Control   | 3.6 ± 0.1 a      | 1.17 ± 0.04 a        | 10.3 ± 0.3 a           | 2.2 ± 0.2 a            | 186 ± 13 a           | 8.4 ± 0.3 b          |
|      | MR        | 3.3 ± 0.1 b      | 1.03 ± 0.03 b        | 9.8 ± 0.1 b            | 1.5 ± 0.1 b            | 157 ± 7 b            | 10.4 ± 0.3 a         |
|      | SR        | 3.0 ± 0.1 b      | 1.01 ± 0.01 b        | 9.6 ± 0.3 b            | 1.4 ± 0.0 b            | 126 ± 3 b            | 9.2 ± 0.3 a          |
| 83   | Control   | 5.2 ± 0.2 a      | 0.91 ± 0.04 a        | 10.3 ± 0.1 a           | 4.3 ± 0.1 a            | 407 ± 9 a            | 9.5 ± 0.1 b          |
|      | MR        | 3.7 ± 0.0 b      | 0.68 ± 0.07 b        | 8.7 ± 0.4 b            | 2.0 ± 0.0 b            | 241 ± 5 b            | 12.2 ± 0.1 a         |
|      | SR        | 3.9 ± 0.1 b      | 0.72 ± 0.04 b        | 9.0 ± 0.2 b            | 2.2 ± 0.0 b            | 260 ± 1 b            | 11.6 ± 0.1 a         |

Each value is shown as the mean ± SE. DAT: days after commencing treatments; z: MR, moderate wilting–full recovery treatment; y: SR, severe wilting–full recovery treatment; x: Different letters in the same columns indicate significant differences among the treatments, as determined using the Tukey–Kramer’s test at p < 0.05 (n = 4).

3.4. Yield

We recorded final accumulated fruit yield per plant of 1.7, 0.9, and 1.0 kg under control, MR, and SR conditions, respectively, with the values obtained for MR and SR plants being 50% and 60% of that in control plants, respectively (Figure 7a). In contrast, the treatments did not significantly differ with respect to the accumulated number of harvested fruits (Figure 7b). However, fruit weight from control plants remained relatively constant throughout the treatment period (Figure 7c), and we observed a reduction in the fruit weight produced by MR and SR plants in response to the water stress conditions applied at the fruit development (32, 46, and 53 DAT) and anthesis (59, 66, 73, and 79 DAT) stages.

Figure 7. Effects of water stress on accumulated fruit yield (a), accumulated number of harvested fruits (b), and fruit weight (c) of tomatoes. In each treatment, fruits were harvested from 5–12 tomato plants at eight time points (20, 32, 46, 53, 59, 66, 73, and 79 days after commencing treatments (DAT)) throughout the experiment. MR: moderate wilting–full recovery treatment; SR: severe wilting–full recovery treatment.
3.5. Fruit Quality

Throughout the experiment, the Brix and acidity values recorded for the control plants showed comparatively little variation (Figure 8). Although there were no significant differences among treatments with respect to the Brix and acidity of tomatoes at the first harvest (20 DAT), the values for fruits obtained from MR and SR plants increased with an increase in treatment time from 32 to 79 DAT (the second to eighth harvests) compared with the control. With the exception of the second and fourth harvest (32 and 53 DAT), we detected no significant differences in the Brix and acidity values between MR and SR. Notably, however, increases in the fruit quality obtained from MR and SR tomatoes were detected in response to the imposition of water stress from the fruit development (32, 46, and 53 DAT) and anthesis (59, 66, 73, and 79 DAT) stages.

![Figure 8](image-url)

**Figure 8.** Effects of days of water stress treatment on the Brix (a) and acidity (b) values of tomato fruits. Fruits were harvested at eight time points (20, 32, 46, 53, 59, 66, 73, and 79 days after commencing treatments (DAT)) throughout the experiment. Each value is shown as the mean ± SE. Different letters indicate significant differences among the treatments, as determined using the Tukey–Kramer’s test at \(p < 0.05\) (\(n = 4–6\)). MR: moderate wilting–full recovery treatment; SR: severe wilting–full recovery treatment.

4. Discussion

4.1. Irrigation Management

Continuous monitoring of the projected leaf area has been established as a relatively straightforward non-destructive method for assessing the wilting of tomato plants [1,15]. In the present study, we were able to digitize and calculate the accumulated wilting ratio to evaluate the amount of water stress associated with the use of the image-based irrigation system, which can be used to modify the irrigation cycle by controlling the threshold value \((W_{set})\) and irrigation amount per time, as illustrated by the diurnal periodic cycle of wilting–full recovery assessed in this study. In this context, Liu et al. [2] reported that although increasing the threshold value for irrigation reduced the irrigation frequency, it did not affect the total irrigation amount when determined by the cumulative evaporation every few days. Consistent with these findings, we similarly found that the timing of irrigation was dependent on the threshold value as the wilting level, and that the higher the irrigation frequency in MR, the lower the accumulated water stress at the same irrigation amount. In addition, we established that despite differences in \(W_{set}\), the total irrigation amounts in MR and SR under the diurnal periodic cycle of wilting–full recovery was the same. Plants with the same leaf areas under the same VPD conditions may receive the same amount of water in MR and SR during the experimental period, despite differences in \(W_{set}\), which could be attributable to the fact that the irrigation amounts in each treatment were adjusted to compensate for the amount of water lost via transpiration during full recovery from wilting. Based on these findings, it would appear that the threshold value influenced
the irrigation frequency and the accumulated wilting ratio, but did not affect the irrigation amount applied when a full-recovery irrigation strategy was adopted after wilting.

4.2. Plant Growth and Photosynthesis

Consistent with the findings of numerous previous studies, which have revealed that water stress contributes to inhibiting plant growth and thus results in lower yields [9–11], we found that plant growth in response to MR and SR was significantly lower than that obtained in the control. The irrigation amount in the MR and SR were 34–40% of that applied in the control, and at the end of the period of experimental irrigation, plants irrigated using the MR and SR schedules had plant lengths, leaf areas, internode lengths, FWs, and DWs that were 72–76%, 75–82%, 84–87%, 46–52%, and 60–64%, those of the control plants, respectively. These findings, thus, indicate that compared with other growth parameters, water stress has a more pronounced effect on plant weight, particularly FW.

When subjected to water stress, tomato leaves typically show reductions in Pn, as has been extensively documented [6–8]. In the present study, although reduced Pn levels were found to recover immediately after irrigation in MR and SR, we suspect that the water stress induced by these treatments may have inhibited leaf area expansion to a certain extent, compared with that of control plants. Moreover, with prolonged exposure to water stress conditions, there was a gradual reduction in the Pn of the entire plants compared to the control plants.

Nevertheless, despite differences in the $W_{set}$ value and irrigation frequency, we detected no difference in the growth of plants subjected to the MR and SR irrigation schedules, which could be ascribed to the fact that plants in these two treatments received similar irrigation amounts. In this regard, previous studies have reported that an increase in the irrigation frequency under the same total irrigation amount per day promoted photosynthesis [19] (p. 403) and tomato yield [20]. Conversely, Harmanto et al. [21] failed to detect any significant effect of an increase in irrigation frequency on tomato yield under the same total irrigation amount per day. In general, the effect of irrigation frequency is determined by the drainage ratio, which is dependent on the water-holding capacity of the substrate. Pires et al. [19] (pp. 402–404) also reported that a high frequency of irrigation with a small amount of water reduced the drainage ratio from a small volume of substrate and increased the amount of irrigation absorbed. Given that in both MR and SR irrigations in the present study all the applied nutrient solutions were absorbed by plants without drainage, the irrigation frequency had no appreciable effect on plant growth.

4.3. Fruit Yield, Quality, and Stress-Effective Development Stage

Nangare et al. [10] reported that in the autumn–winter seasons of 2 years, the yield of tomatoes subjected to water stress treatment, where the irrigation amount was 65% of that lost by the crop via evapotranspiration, was 73% and 80%, respectively, of that of control plants that received sufficient irrigation. Wang et al. [23] reported that when irrigating in winter–spring seasons with an irrigation amount of 70% that of crop water consumption during fruit maturation stages, tomato yield was 75% of that in the control with sufficient irrigation, whereas no comparable reductions were recorded in spring–summer seasons. Comparatively, in the present study, the total irrigation amounts applied in the MR and SR were approximately 34% and 40% of the control amount, respectively, which gave rise to respective tomato yields of approximately 50% and 60% of that obtained with control irrigation. These results indicated that tomato yield was dependent on the total irrigation amount, and that proportionally, yield reductions were lower than the corresponding reductions in the total irrigation amount.

Most studies that have examined these effects and reported that reductions in yield due to water stress are manifested as reductions in the number and weight of tomato fruits [24,25]. In contrast, in the present study, we recorded no significant reductions in fruit number, which could be attributed to the fact that our spraying of plants with hormones at anthesis stage contributed to preventing flower failure and/or the early drop of small
fruits. Consequently, it appears that in both MR and SR, the main factor contributing to the observed yield reductions was lower fruit weight.

The amount and timing of irrigation affect not only fruit yield, but also the fruit quality of tomatoes [20]. Machado and Oliveira [26] reported that reductions in the irrigation amount contributed to an increase in the Brix values of tomato fruits. Consistently, in the present study, compared with control plants, we recorded similar higher Brix values for fruits obtained in response to the MR and SR irrigation schedules, despite differences in the threshold value. These findings indicate that increases in Brix in response to water stress are mainly attributable to a reduction in irrigation amount, and not to differences in the irrigation frequency or cumulative wilting ratio. Based on the results obtained for acidity and fruit weight in response to the MR and SR treatments, it appears that the similar total irrigation amounts in these two treatments also led to similar qualities of the resulting fruits.

From the perspective of enhancing the fruit quality of tomatoes, knowledge of the most appropriate fruit stage at which to commence water stress treatment is particularly beneficial, and numerous studies have reported on the optimum stage, for example, from anthesis to the fruit-ripening stage of the first cluster [3], during the fruit maturation stage [22], and during early fruit development, earlier than 2 to 3 weeks prior to harvest [27]. In the present study, we found that commencing water stress treatment from anthesis stage or the early fruit development stage was an effective strategy for improving fruit quality, whereas commencing treatment at the fruit ripening to mature stage was ineffective. Furthermore, these findings indicate that water stress treatment should be maintained throughout the cultivation period to enhance the fruit quality on all trusses, given the successive pattern of anthesis on different trusses.

Although we established that the threshold values and irrigation frequencies differed in the MR and SR irrigation schedules, similar total irrigation amounts contributed to comparable values for plant growth, fruit quality, and tomato yield when using these two treatments. Based on these findings, we suggest that the total irrigation amount is a more important parameter than the threshold value, irrigation frequency, or cumulative wilting ratio in determining the growth, yield, and fruit quality of tomatoes.

5. Conclusions

In this study, we demonstrated the usefulness of the automatic irrigation method based on a diurnal periodic cycle of wilting–full recovery, which controls the wilting level and irrigation amount per time in the production of high-quality tomatoes in a greenhouse. The total irrigation amount, photosynthesis, growth, and yield decreased, and fruit quality increased in the moderate and severe wilting-full recovery treatments compared with the control. There were no significant differences in these parameters between the two water stress treatments. The net photosynthetic rate decreased under water stress and recovered rapidly to more than 90% of its maximum value following irrigation. Collectively, our findings indicated that the total irrigation amount was a more important parameter than the threshold value, irrigation frequency, or cumulative wilting ratio in determining the growth, yield, and fruit quality of tomatoes. Moreover, commencing water stress treatment at the anthesis stage or early fruit development stage could represent an effective strategy for enhancing fruit quality.

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