Article

Efficient Water Management for Cymbidium Grown in Coir Dust Using a Soil Moisture Sensor-Based Automated Irrigation System

Seong Kwang An [1], Hyo Beom Lee [1,2], Jongyun Kim [3] and Ki Sun Kim [1,2,*]

1   Department of Horticultural Science and Biotechnology, Seoul National University, Seoul 08826, Korea; ahnsungkwang@snu.ac.kr (S.K.A.); hyobumi1003@snu.ac.kr (H.B.L.)
2   Research Institute of Agricultural and Life Sciences, Seoul National University, Seoul 08826, Korea
3   Department of Plant Biotechnology, Korea University, Seoul 02841, Korea; jongkim@korea.ac.kr
*   Correspondence: kisun@snu.ac.kr

Abstract: Efficient long-term management for the production of high-quality *Cymbidium* plants is required as these orchids generally require 3–4 years of vegetative growth to allow flowering. This study was conducted to investigate the optimal substrate moisture levels to efficiently produce young cymbidium using a soil moisture sensor-based automated irrigation system over 42 weeks of vegetative growth. One-year-old cymbidium "Hoshino Shizuku" plantlets were grown in coir dust substrate at four levels of volumetric water content (0.25, 0.35, 0.45, and 0.55 $m^3 \cdot m^{-3}$). At harvest, the numbers of leaves and pseudobulbs, and the chlorophyll content of the cymbidiums did not differ among the four θ threshold treatments. However, plants grown at 0.25 $m^3 \cdot m^{-3}$ had significantly smaller leaves, pseudobulbs, and biomass than those at the other θ threshold treatments. Although the lower θ decreased the photosynthetic parameters, such as the net photosynthesis, stomatal conductance, and transpiration, there were no differences in the maximum quantum yield of photosystem II, indicating that the reduction in net photosynthesis is mostly mediated by stomatal closure. Although the net photosynthesis at θ of 0.35 $m^3 \cdot m^{-3}$ was also lower than that at 0.55 $m^3 \cdot m^{-3}$ treatment, biomass was significantly lower only at 0.25 $m^3 \cdot m^{-3}$ treatment, suggesting that a critical growth reduction by the water deficit occurred for the cymbidium at 0.25 $m^3 \cdot m^{-3}$. As the θ threshold increased, the total irrigation amount significantly increased, which inversely decreased the water use efficiency. Although the plants grown at 0.25 $m^3 \cdot m^{-3}$ had the highest water use efficiency (WUE) and substrate electrical conductivity they showed significantly reduced growth compared to other θ threshold treatments, and thus this was not a reliable θ threshold level for producing high (visual) quality cymbidium. Overall, the 0.35 and 0.45 $m^3 \cdot m^{-3}$ threshold treatments provided appropriate moisture levels for high-quality cymbidium production with high water use efficiency.

Keywords: efficient irrigation; drought; orchids; photosynthesis; soil moisture sensor; water use efficiency

1. Introduction

Orchids are one of the most commercial floricultural crops and are distributed throughout the world. In international flower trade, orchids rank sixth among the top ten cut flowers, while cymbidium (*Cymbidium* spp.) ranks first among the orchid species [1]. Although the price of orchids has been lowered due to technological advances in micropropagation, they are still relatively expensive for flowers as, for example, cymbidium requires cultivation periods of ca. 4–5 years to grow from seedlings to cut flowers or potted plants; efficient long-term management is therefore necessary for profitable cymbidium production [2].

Flowering and quality of cymbidium have been attempted to be improved by controlling environmental factors such as temperature, light intensity, photoperiod, substrate,

and nutrient [3–5] to allow more efficient cymbidium production practice. Bark, which provides macropores, is commonly used in the commercial production of cymbidium having a specialized root structure with a velamen layer susceptible to high moisture conditions. Most cymbidium growers use bark as the substrate to avoid over wet conditions, thus preventing rhizosphere diseases, including root rot, black rot, or bacterial infections, this substrate, which has a low water-holding capacity, requires more frequent irrigation with a huge drainage fraction [6]. Alternative substrates with a higher water-holding capacity have been investigated to enhance water and nutrient use efficiency; better cymbidium growth was subsequently observed in cymbidium grown in carbonized rice hull [7], peat moss [8], and Hyuga pumice [9] than those grown in the bark. Nevertheless, most orchid growers are reluctant to change their substrate because of the difficulty of irrigation management on substrates with a high water-holding capacity. Although most standard type commercial cymbidiums are classified as terrestrial (C_3 plant) which prefer slightly moistened substrate conditions than epiphytic (CAM plant) cymbidium [10], most cymbidium growers in Korea usually irrigate with timer-based irrigation using a sprinkler, and approximately 75% of the water with dissolved fertilizer is leached every irrigation [11].

Recently developed soil moisture sensor technology has enabled more effective irrigation by precisely providing water for plants when needed, thus improving water and nutrient use efficiency in horticultural crops, such as *Hibiscus acetosella* "Panama Red" [12], *Gaura lindherimeri* [13], and *Ocimum basilicum* [14]. Many researchers who have implemented soil moisture sensor-based irrigation systems were able to save a considerable amount of water usage while securing the marketable quality of their plants [15–17]. These systems not only reduced water use, but also reduced pathogen susceptibility by favoring the rhizosphere environment for *Gardenia jasminoides* [18]. By adopting this soil moisture sensor-based automated irrigation system in cymbidium production, favorable conditions could be provided for the specialized root of cymbidium, while increasing water use efficiency (WUE) when grown in fine substrates other than bark. Therefore, this study was conducted (1) to investigate the influences of substrate moisture levels on the growth of young cymbidium "Hoshino Shizuku" using a soil moisture sensor-based automated irrigation system, and (2) to determine the suitable substrate water content for growing cymbidium to increase WUE.

2. Materials and Methods

### 2.1. Plant, Substrate Materials and Growth Conditions

One-year-old cymbidium "Hoshino Shizuku" plantlets (Bio-U. Ltd., Zentuji, Kagawa, Japan) were obtained from a commercial orchid nursery (Haepyeong Orchids Farm, Gongju, Korea) on 29 March 2019. The plants were manually watered for 5 weeks to acclimate them to the experimental greenhouse environment, which is located in Seoul National University Farm, Suwon, Korea. After washing of the roots, the plants were transplanted in 1330 mL plastic pots (15 by 13 cm, diameter by height), filled with coir dust (Satis International Co., Ltd., Seoul, Korea; originated from Sri Lanka). After transplanting, plants were placed in the same greenhouse and carefully managed for two months to acclimate them and allow root stabilization in the new substrates. Plants were fully irrigated on 29 June 2019 and were then not irrigated until the automated irrigation began on 3 July. During the experiment, plants were provided with a 15N-4.8P-10.8K + 2Mg + TE controlled-release fertilizer (Osmocote Plus; Everris International B.V., Heerlen, The Netherlands) at four g/pot. The fertilizer was applied to the surface of each substrate when automated irrigation treatment was initiated.

When the treatments began on 29 June, the number of leaves, length, and width of the uppermost fully expanded leaf, the longest pseudobulb diameter, and chlorophyll content were 17.2 ± 0.28 (mean ± SE, n = 12), 44.1 ± 0.64 cm, 2.0 ± 0.01 cm, 20.1 ± 0.37 mm, and 55.7 ± 1.40, respectively. The experiment was carried out for 42 weeks, from 29 June 2019 to 17 April 2020. The temperature, vapor pressure deficit, and daily light integral inside the

greenhouse were monitored using a temperature and humidity sensor (VP-3; Meter Group, Pullman, WA, USA) and a photosynthetic active radiation sensor (SQ-110-SS; Apogee Instruments, Logan, UT, USA) connected to a data logger (CR1000; Campbell Scientific, Logan, UT, USA). During the experiment, the average daily temperature, relative humidity, vapor pressure deficit, and daily light integral in the greenhouse were 19.2 ± 2.9 °C (mean ± SD), 67.4 ± 8.2%, 1.5 ± 0.0 kPa, and 3.7 ± 1.6 mol·m^{-2}·d^{-1}, respectively.

2.2. Physical Properties of the Substrate

The moisture retention curve of the substrate was determined using a Hyprop (Meter Group, Pullman, WA, USA) to investigate the proper irrigation threshold volumetric water content (θ, *v/v*) level for the coir dust used in the current experiment (Figure 1). Each θ threshold set point for irrigation was determined in the range around easily available water (from −1 to −5 kPa suctions) and water buffering capacity (from −5 to −10 kPa suctions) for the coir dust [19], and the setpoint for irrigation θ thresholds were determined as 0.25, 0.35, 0.45, and 0.55 m^3·m^{-3}, which are −15.0, −5.0, −2.6, and −1.6 kPa, respectively (Figure 1). Because cymbidium must avoid wet substrate conditions which can cause root rot diseases, we set the θ threshold from the bottom of the available water content.
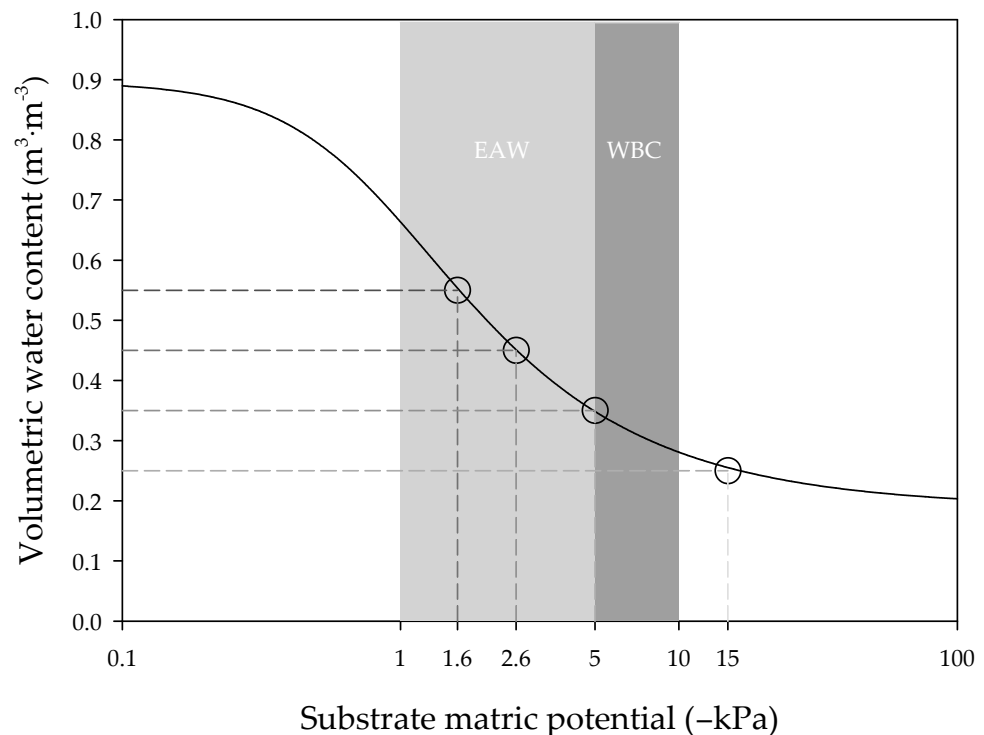
Figure 1. Moisture retention curve of the coir dust substrate used in this study using Hyprop (Meter Group, Pullman, WA, USA). The irrigation θ thresholds were set at −1.6, −2.6, −5.0, and −15.0 kPa, representing water contents of 0.55, 0.45, 0.35, and 0.25 m^3·m^{-3}, respectively, within range of easily available water (EAW) and water buffering capacity (WBC). Each point indicates the relationship between setpoints and substrate matric potential.

2.3. Frequency Domain Reflectometry (FDR) Sensor-Based Automated Irrigation System

FDR uses the electrical properties of soil of substrate at a specific frequency to determine dielectric constant of the substrate [20]. The dielectric constant is related to the θ of the substrate based on the difference in the dielectric constants of water and substrate [21]. To measure and control the θ in the pots, twelve FDR soil moisture sensors (EC-5; Meter Group), were connected to a data logger (CR1000; Campbell Scientific). To acquire better resolution of θ, the soil moisture sensors were powered by 2.5 V through VX ports of the data logger. Substrate-specific calibration was conducted according to the equation;

θ = 0.1667 × sensor output in mV − 54.446 (r^2 = 0.89). Each sensor (5.5 cm length and 1.0 cm width) was inserted diagonally from the top of the substrate in the middle of a pot, where the roots were located, to a depth of ca. 6.0 cm. The data logger was connected to a relay driver (SDM-CD16AC; Campbell Scientific) which controlled the power to 12 solenoid valves (NaanDanJain Irrigation Ltd., Rehovot, Israel). Each experimental unit had five plants as sub-replicates, and the θ was measured for one pot in the center for each experimental unit. Every 20 min, if the θ reading of the FDR sensors in an experimental unit dropped below the assigned θ threshold, the data logger opened the solenoid valve to the experimental unit for 20 s. Each pot was irrigated using a spray stake (PC Spray Stakes; Netafim, Tel Aviv, Israel), and five spray stakes were connected to one of pressure-compensated drip emitter (PCJ HF-20L, Netafim). Each irrigation event provided ca. 20 mL. Each irrigation application was recorded by a data logger, and the daily and total amount of water applied to the plants were subsequently calculated.

2.4. Plants Growth Parameters and WUE

After 42 weeks of treatment, the total number of leaves, the length and width of the uppermost fully expanded leaf, and the fresh and dry weights of shoots and roots were measured. The pseudobulb diameter was measured at the widest point of the pseudobulb using a digital vernier caliper (ABS Digimatic Caliper; Mitutoyo Co., Ltd., Tsukuba, Japan). Chlorophyll content was measured from the uppermost fully expanded leaves using a chlorophyll meter (SPAD 502; Minolta, Osaka, Japan). Dry weights were determined after drying the samples in an oven at 80 °C for 7 d. WUE of the plants was calculated as the total dry weight of the plants (in g) divided by the water use, as calculated from the automated irrigation system [22].

2.5. Photosynthetic Gas Exchange and Chlorophyll Fluorescence

Photosynthetic gas exchange was measured using a portable photosynthesis measuring system (Li 6400; Li-Cor Co., Inc., Lincoln, NE, USA) from 11:00 to 13:00 for one week after 41 weeks of growth. Three plants per experimental unit were randomly selected and used for measurement. The uppermost mature leaf was clamped onto a 6 cm^2 LED head chamber with a photosynthetic photon flux density of 1000 $\mu mol \cdot m^{-2} \cdot s^{-1}$. The relative humidity and temperature in the chamber were maintained at 60–75% and 20 °C, respectively. The rate of airflow through the chamber was 500 $mL \cdot min^{-1}$ with a CO_2 level of 400 $\mu mol \cdot mol^{-1}$. After a steady-state gas exchange was achieved, the net photosynthetic assimilation rate (A_n), stomatal conductance (g_s), and transpiration (E) were determined.

Chlorophyll fluorescence of the uppermost mature leaves was measured using a chlorophyll fluorometer (PAM 2000; Heinz Walz, Effeltrich, Germany) after 41 weeks of treatment. Three plants were measured in each treatment. The uppermost fully expanded leaves were chosen for measurement to avoid the main vein. Before each measurement, the leaf was dark-adapted for 30 min. The minimal (F_o) and maximal fluorescence (F_m) were measured using modulated irradiation and a 0.8 s saturating pulse, respectively. Actinic light was switched on after 40 s; subsequently, a saturating pulse was turned on every 20 s for 6 min to determine the maximal fluorescence in the irradiation-adapted state (F_m). The formula of *Fv/Fm* was $Fv/Fm = (F_m − F_o)/F_m$.

2.6. Experimental Design and Statistical Analysis

The experiment used a randomized complete block design with four treatments and three blocks. The chemical properties of the substrates and the effects of the substrates on the growth and development parameters at harvest were analyzed using analysis of variance, followed by Duncan's multiple range test at α = 0.05, using SAS 9.4 (SAS Institute, Cary, NC, USA). Regression analysis was used for the substrate-specific θ calibration and to investigate the relationships between electrical conductivity and the θ threshold treatments using SigmaPlot (SigmaPlot 11.0, Systat Software Inc., San Jose, CA, USA).

3. Results and Discussion

3.1. Performance of the FDR Sensor-Based Automated Irrigation System

The FDR sensor-based automated irrigation system properly maintained the θ of the treatments as planned for 42 weeks (Figure 2). Although the lower θ threshold treatment (0.25 and 0.35 $m^3 \cdot m^{-3}$) decreased θ gradually without irrigation for a week after the automated irrigation system was initiated, all of the treatments were irrigated when θ dropped below the designated θ threshold. Because the θ in each pot was consistently maintained just above the allocated threshold throughout the experiment, the θ values during the 42 weeks were 0.28 ± 1.0, 0.38 ± 1.2, 0.49 ± 1.4, and 0.58 ± 0.8 $m^3 \cdot m^{-3}$ (mean ± SD) for the 0.25, 0.35, 0.45, and 0.55 $m^3 \cdot m^{-3}$ θ threshold treatments, respectively. These SD values were somewhat larger than the previous study where SD was less than 0.01 $m^3 \cdot m^{-3}$ [14]; this is mostly due to the use of the spray stake irrigation method used in the current experiment. However, the automated irrigation system provided a reliable θ threshold treatment to quantify the effect of θs on cymbidium growth and water use grown in coir dust.
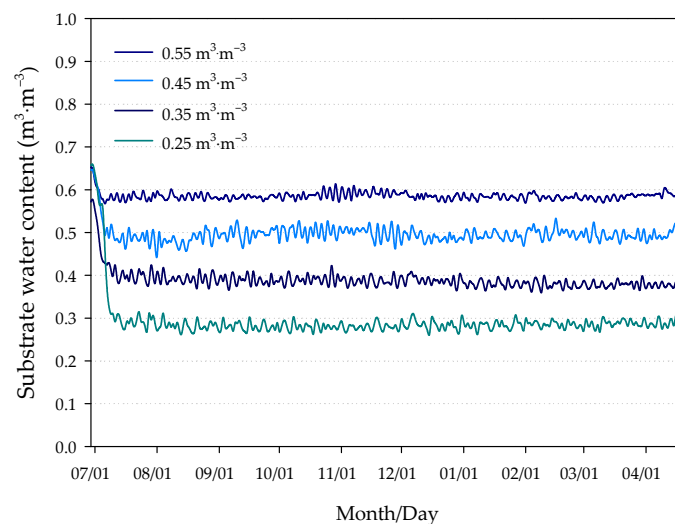
Figure 2. Substrate volumetric water content of 1-year-old cymbidium "Hoshino Shizuku" as maintained by a sensor-based automated irrigation system with coir dust substrate for 42 weeks. Plants were irrigated when the substrate water content reading of the FDR sensors dropped below each 0.25, 0.35, 0.45, and 0.55 θ thresholds ($m^3 \cdot m^{-3}$).

3.2. Vegetative Growth of Cymbidium

Over 42 weeks of cymbidium growth with the four different θ threshold treatments, only plants in the 0.25 $m^3 \cdot m^{-3}$ treatment showed relatively smaller leaves and pseudobulbs than those at higher θ threshold treatments, but the numbers of leaves and pseudobulb and chlorophyll contents were similar regardless of the θ treatments (Table 1 and Figure 3). The leaf size (length and width) of the plants was significantly smaller at 0.25 $m^3 \cdot m^{-3}$ treatment than those at the higher θ threshold treatments (0.45 and 0.55 $m^3 \cdot m^{-3}$), indicating that lower θ limits their leaf expansion. In general, meristem activity and the turgor required for cell expansion are affected by water availability, and drought or reduced water conditions may limit leaf size [23,24]. Several ornamental crops, such as *Heuchera americana*, *Gaura lindheimeri*, and petunia, showed a similar tendency, with smaller leaf areas when exposed to drought conditions [13,16,25]. The pseudobulb is an essential and specialized organ of several orchid species used to store photosynthetic assimilates and water, thus consequently producing a series of adjacent shoots that continue to grow until they bloom [26,27]. In addition, stored water in pseudobulbs can help cymbidium tolerate drought stress [28,29]. Although the plants grown under the 0.25 $m^3 \cdot m^{-3}$ treatment produced a similar number of pseudobulbs, these pseudobulbs were significantly smaller

than those from plants grown under the other θ threshold treatments. This indicates that the 0.25 m^3·m^{-3} treatment mimicked water deficit conditions, and thus reduced the growth of cymbidium pseudobulbs. Although a decline in chlorophyll content under drought has often been reported for several species, such as *Olea europaea*, *Periploca angustifolia*, and *Doritaenosis* [30–32], cymbidium grown with various θs displayed similar SPAD values, for 42 weeks, regardless of the θ threshold treatments. Likewise, Zheng et al. [29] reported that the 1-year-old leaves of cymbidium did not change their chlorophyll content under drought conditions, while 2-year-old leaves decreased the chlorophyll content by drought, indicating that the growth stage of the leaves is important for the decline in chlorophyll content of cymbidium leaves.

Table 1. Vegetative growth characteristics of 1-year-old cymbidium "Hoshino Shizuku" with a frequency domain reflectometry (FDR) sensor-based irrigation system for 42 weeks as influenced by different substrate volumetric water content (θ) thresholds (m^3·m^{-3}).

θ Threshold (m^3·m^{-3})	No. of Leaves	Leaf Length (cm)	Leaf Width (cm)	No. of Pseudobulbs	Pseudobulb [z] Diameter (mm)	Chlorophyll Content
0.55	24.3	48.43 a [y]	2.38 a	2.2	34.19 ab	58.11
0.45	23.6	48.20 a	2.34 ab	2.1	35.57 a	55.79
0.35	25.2	45.80 ab	2.23 bc	2.4	33.98 ab	55.41
0.25	22.0	45.07 b	2.16 c	2.3	31.65 b	58.65

[z] Primary pseudobulb was the first formed pseudobulb after deflasking. [y] Mean separation among the θ threshold treatments followed analysis of variance (ANOVA) with Duncan's multiple range test at α = 0.05.
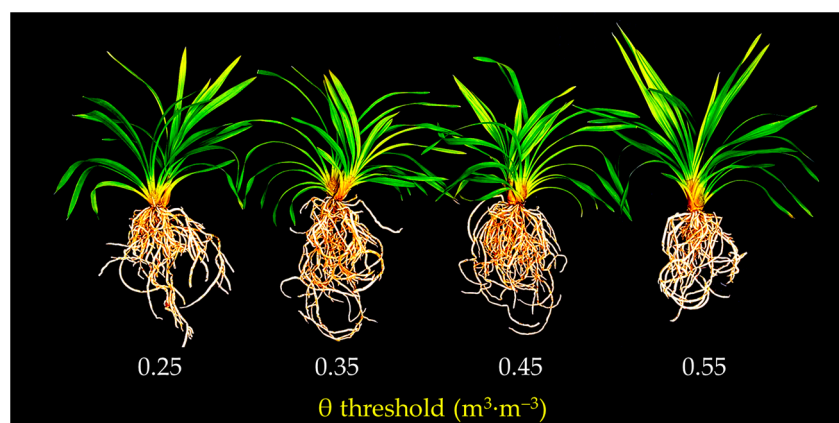
Figure 3. Growth of 1-year-old cymbidium "Hoshino Shizuku" grown under 0.25, 0.35, 0.45, and 0.55 θ thresholds (m^3·m^{-3}) using FDR sensor-based automated irrigation system at harvest after 42 weeks of cultivation.

As the lower θ threshold treatment reduced the leaf and pseudobulb size of cymbidium, the θ threshold treatment affected the fresh and dry weights of pseudobulbs, shoots, and roots of cymbidium (Table 2). Among the θ threshold treatments, all biomass parameters were the lowest at 0.25 m^3·m^{-3}, indicating the adverse effect of drought. In particular, both shoot fresh and dry weights of cymbidium grown at θ of 0.25 m^3·m^{-3} were significantly lower, displaying 15% and 5% lower fresh and dry shoot weights than those of the other higher θ treatments, respectively, whereas the plants grown at the higher θ threshold treatments all had similar values. In addition, the fresh and dry weights of pseudobulbs and roots of cymbidium grown at 0.25 m^3·m^3 were the lowest, displaying ca. 22 and 5% less dry weight than the averages of the other θ threshold treatments in the pseudobulb and root, respectively. These results indicate a significant reduction in biomass accumulation at θ of 0.25 m^3·m^{-3}, whereas the other, higher θ threshold treatments showed similar biomass values. Currey et al. [33] reported that parsley, basil, and dill decreased their biomass linearly when they received θ from 0.45 m^3·m^{-3} to 0.15 m^3·m^{-3}, and Nam et al. [14]

reported that basil grown at 0.45 $m^3 \cdot m^{-3}$ even had lower biomass than those grown at 0.60 $m^3 \cdot m^{-3}$. For the ornamental plants, *Hibiscus acetosella*, *Gaura lindheimeri*, *Lavandula angustifolia*, *Heuchera americana* exhibited linear decreases in biomass, with a decreasing θ threshold, when grown at various θ values from 0.50 to 0.15 $m^3 \cdot m^{-3}$ [13,25,33]. In the current study, 0.25 $m^3 \cdot m^{-3}$ treatment only displayed the significant reduced biomass, but the plants grown at 0.35 $m^3 \cdot m^{-3}$, which was regarded as a drought condition for other species, had no reduction of biomass compared to those grown at higher θ threshold treatments.

Table 2. Fresh and dry weight of 1-year-old cymbidium "Hoshino Shizuku" grown with FDR sensor-based irrigation system for 42 weeks, as influenced by 0.25, 0.35, 0.45, and 0.55 θ thresholds ($m^3 \cdot m^{-3}$).

| θ Threshold ($m^3 \cdot m^{-3}$)	Fresh Weight (g)			Dry Weight (g)		
	Pseudobulb [z]	Shoot	Root	Pseudobulb	Shoot	Root
0.55	15.45 ab [y]	110.74 a	133.36 ab	3.43 a	37.13 a	29.57 a
0.45	17.21 a	105.93 a	138.96 a	3.59 a	35.86 a	29.83 a
0.35	14.82 ab	101.10 a	136.63 ab	3.20 ab	35.04 a	29.66 a
0.25	12.54 b	90.00 b	120.11 b	2.64 b	32.73 b	28.21 b

[z] Primary pseudobulb was the first formed pseudobulb after deflasking. [y] Mean separation among the θ threshold treatments followed ANOVA with Duncan's multiple range test at α = 0.05.

The relationship between θ and growth also showed apparent differences in many studies, even though their test period was relatively shorter than that in this study. For example, the dry mass of English lavender "Munstred", grown at a θ of 0.1 $m^3 \cdot m^{-3}$ was 57% lower than that at 0.4 $m^3 \cdot m^{-3}$ for 54 d of treatment [34]. Currey et al. [33] reported that the dry shoot mass of sage increased three times as θ increased from 0.15 to 0.45 $m^3 \cdot m^{-3}$ to 28 d. Most orchids generally have a slower growth over a long period because of their genetic characteristics and reduced photosynthetic capacity [35,36]. Our study was conducted for 42 weeks, which is a relatively long period for the irrigation study of horticultural crops, and we found that even the lowest θ threshold treatment could maintain the growth of cymbidium. Although dramatic growth changes were not observed in cymbidium across the θ threshold treatments compared with the other horticultural crops, a θ value higher than 0.35 $m^3 \cdot m^{-3}$ could be suggested for long-term cymbidium cultivation to secure high crop quality, as growth under 0.25 $m^3 \cdot m^{-3}$ may decrease the growth of the shoot, root, and pseudobulb of cymbidium. In particular, pseudobulb growth is very critical during the young orchid cultivation period, as the pseudobulb size is positively related to flowering quality in orchids, including *Cymbidium*, *Dendrobium*, and *Miltoniopsis* [2,37,38].

3.3. Photosynthetic Gas Exchange and Chlorophyll Fluorescence

Although the shoot dry weight result displayed a reduction in growth only under the 0.25 $m^3 \cdot m^{-3}$ treatment, the lower θ threshold levels significantly resulted in decreased photosynthetic parameters (A_n, g_s, and E) of cymbidium (Figure 4, $p < 0.001$). All photosynthetic parameters of cymbidium grown at 0.25 $m^3 \cdot m^{-3}$ were the lowest among the θ threshold treatments, showing that limited substrate moisture led to reduced stomatal opening, thus reducing photosynthesis. The photosynthetic parameters of cymbidium grown at 0.45 and 0.55 $m^3 \cdot m^{-3}$ were similar, but the 0.35 $m^3 \cdot m^{-3}$ treatment showed lower g_s and E values than those of the higher θ treatments. However, the parameters of plants grown under the 0.35 $m^3 \cdot m^{-3}$ treatment were not different from that of the 0.45 $m^3 \cdot m^{-3}$ treatment, thus supporting the previous results with similar biomasses. Several studies have reported that a lower θ condition as drought could limit photosynthesis by restricting their gas exchange via stomatal closure in various plants compared to higher θ conditions [14,33,39]. In addition, in other orchid species, the lower θ gradually decreased A_n, g_s, and E of *Doritaenopsis* "Mantefon", which is classified as CAM plant, with the θ threshold decreasing from 0.5 to 0.2 $m^3 \cdot m^{-3}$ [32].
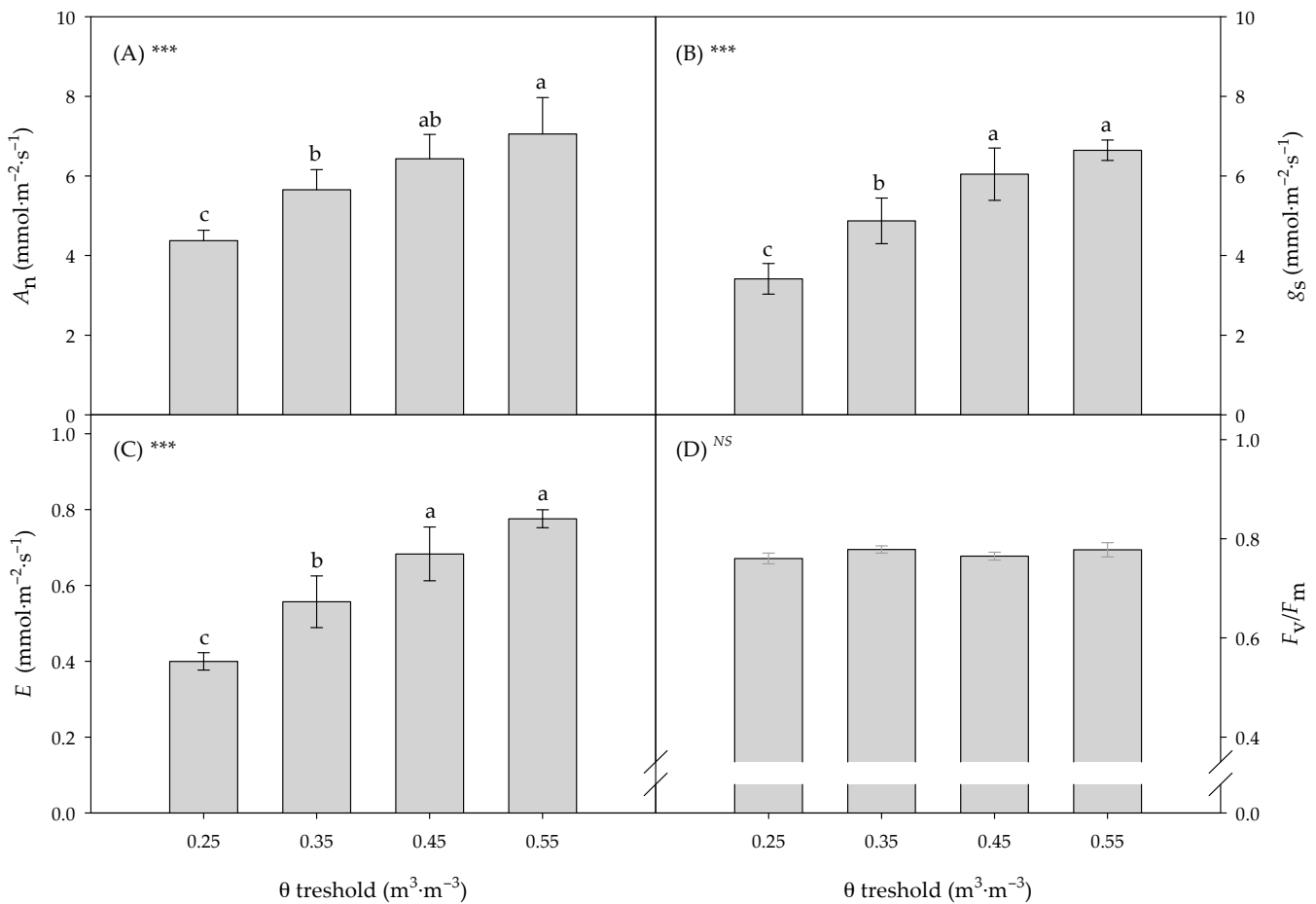
Figure 4. Net CO_2 assimilation rate (A_n, (**A**)), stomatal conductance (g_s, (**B**)), transpiration rate (E, (**C**)), and maximum quantum efficiency of photosystem II (F_v/F_m, (**D**)) in the uppermost mature leaves of 1-year-old cymbidium "Hoshino Shizuku" after 41 weeks under 0.25, 0.35, 0.45, and 0.55 θ thresholds ($m^3 \cdot m^{-3}$). Mean separation by Duncan's multiple range test at $\alpha = 0.05$. ^{NS} and *** indicate non-significance and significance at $p < 0.001$. Error bars indicate SE ($n = 9$).

Although there was a significant difference in A_n among the treatments, the maximal quantum efficiency of photosystem II (F_v/F_m) did not differ across the θ threshold treatments (Figure 4D), indicating that no damage to photosystem II occurred due to the θ treatments during the experimental period, and the limited A_n, g_s, and E at 0.25 $m^3 \cdot m^{-3}$ were mostly due to the stomatal response to drought conditions. In general, when plants were exposed to drought conditions, they immediately close their stomata to prevent any water loss that could affect photosynthetic gas exchange. Previously, Kim et al. [40] reported that reduced the A_n and g_s of petunia exposed to mild (0.2 $m^3 \cdot m^{-3}$) and moderate (0.3 $m^3 \cdot m^{-3}$) drought conditions could partially recover while maintaining their θ threshold levels, showing the acclimation ability of the plants. However, cymbidiums grown at θ of 0.25 and 0.35 $m^3 \cdot m^{-3}$ showed reduced g_s and E, even when grown for 42 weeks in this study. Previous studies have reported that orchids such as cymbidium, *Cattleya*, and *Oncidium* could withstand severe drought stress because of their unique roots, with a velamen layer and cortex, and their water-storing pseudobulb [10,28]. The pseudobulb serves as a buffer against drought stress because of its ability to retain water [26]. For example, the water contents of the leaf, root, and pseudobulb remained at 63–70% for 42 d of drought conditions in cymbidium [29]. He et al. [41] also reported that pseudobulbs may slow the reduction in leaf water content and water potential during drought stress. Similarly, our results showed that the 0.25 $m^3 \cdot m^{-3}$ treatment decreased the g_s and E values, but they could maintain their growth with reduced A_n and biomass. Meanwhile, the A_n of the 0.35 $m^3 \cdot m^{-3}$ treatment could be acclimated to have similar values to that of the

0.45 m^3·m^{-3} treatment, thus producing similar pseudobulb and biomasses to those at higher θ threshold treatments; indicating that this could be an efficient θ level to produce quality young cymbidium with a sufficient growth.

3.4. WUE

As the irrigation amount decreased with the decreasing θ threshold, the WUE increased inversely and proportionally (Table 3). Although the total volume of water applied at 0.25 m^3·m^{-3} was only 48% of that used by the plants grown at 0.55 m^3·m^{-3}, which showed the highest WUE, the plants at the lowest θ threshold treatment displayed poor biomass productivity compared to the other θ threshold treatments. In addition, plants grown under both the 0.35 and 0.45 m^3·m^{-3} treatments had significantly higher WUE with similar biomasses and reduced water use compared to the 0.55 m^3·m^{-3} treatment. In general, WUE is enhanced by deficit irrigation in various crops [42–44]. Burnett and van Iersel [13] also reported that *Gaura lindheimeri* survived at a θ ranging from 0.10 to 0.45 m^3·m^{-3}, and the WUE of the plants increased with decreasing θ thresholds. Nevertheless, these researchers recommended a θ of 0.25 m^3·m^{-3} as the optimum θ threshold following consideration of water use and marketable plant quality. Similarly, production of marketable *Hibiscus acetosella* can be achieved when the plants are grown at a moderate θ threshold of 0.35 m^3·m^{-3}, even though the plants also withstand their growth at 0.10 m^3·m^{-3} [12]. Therefore, in order to recommend an optimal θ threshold set point, not only water usage, but also the quality of crop growth should be considered. In the case of cymbidium, maintaining a θ threshold ranging from 0.35 to 0.45 m^3·m^{-3} produced high-quality cymbidium with comparatively little water.

Table 3. Irrigation amount, water use efficiency (WUE) of 1-year-old cymbidium "Hoshino Shizuku" at the harvest after 42 weeks of treatments, as influenced by 0.25, 0.35, 0.45, and 0.55 θ thresholds (m^3·m^{-3}).

θ Threshold (m^3·m^{-3})	Irrigation Amount (mL)	WUE (g·mL^{-1})
0.55	2707 a [z]	2.7 c
0.45	2060 b	3.5 b
0.35	1727 c	3.9 b
0.25	1307 d	5.0 a
Significance	***	***

[z] Means separation among the θ threshold treatments followed ANOVA with Duncan's multiple range test at $\alpha = 0.05$. *** indicates significant difference at $p < 0.001$.

4. Conclusions

Our study showed that the soil moisture sensor-based automated irrigation system could be successfully adapted to aid the growth of young cymbidium "Hoshino Shizuku" without any root diseases and irrigation management difficulty, even though coir dust has a higher water holding capacity than bark, conventionally used substrate in commercial orchid production. Most orchid growers are reluctant to use a fine particle substrate because of the difficulty to manage irrigation precisely. However, although coir dust was used as a fine substrate in the current study, it could provide sufficient aeration for the rhizosphere without any root diseases caused by overwatering or a high moisture condition. In addition, θ thresholds higher than 0.35 m^3·m^{-3} provided adequate θ values for plant growth and photosynthesis, and the 0.35 and 0.45 m^3·m^{-3} treatments showed reasonable WUE considering the irrigation amount and biomass, thus maintaining the coir dust substrate at a θ of 0.35 or 0.45 m^3·m^{-3} produced quality young cymbidium. Consequently, if a precision irrigation system using a soil moisture sensor is used, it will not only be able to save water use but also produce high-quality cymbidium plants.

Like the efficient θ threshold treatments included in the easily available water (EAW) range, the matric potential ranges from −5 to −2.6 kPa could be considered when a grower decides the irrigation set point for producing cymbidium using a precision automated

irrigation system with a fine substrate. Meanwhile, our study conducted a relatively short-term period of 42 weeks using the early stage of cymbidium compared with the whole cymbidium cultivation period. Therefore, further studies examining the long-term effects of θ on growth, flowering, and growth stages would be needed for quality cymbidium production strategy with more efficient water use.

References

1. De, L.C. Good agricultural practices of commercial orchids. *Vigyan Varta* **2020**, *1*, 53–64.
2. Kim, Y.J.; Lee, H.J.; Kim, K.S. Night interruption promotes vegetative growth and flowering of *Cymbidium*. *Sci. Hortic.* **2011**, *130*, 887–893. [CrossRef]
3. Barman, D.; Naik, S.K. Effect of substrate, nutrition and growth regulator on productivity and mineral composition of leaf and pseudobulb of Cymbidium hybrid "Baltic Glacier Mint Ice". *J. Plant Nutr.* **2017**, *40*, 784–794. [CrossRef]
4. Ohno, H.; Kako, S. Development of inflorescences in *Cymbidium* (Orchidaceae). *Environ. Control Biol.* **1978**, *16*, 81–91. [CrossRef]
5. Pun, A.B. Growth and flowering response of cymbidium orchid (*Cymbidium erythrostylum*) in different potting media, NPK and sucker management. *Asian J. Res. Agric. For.* **2019**, *2*, 1–6. [CrossRef]
6. Hanson, A.-M.; Harris, J.R.; Wright, R.; Niemiera, A.; Persaud, N. Water content of a pine-bark growing substrate in a drying mineral soil. *HortScience* **2004**, *39*, 591–594. [CrossRef]
7. Won, J.Y.; Lee, Y.R.; Kim, M.S.; Jeoung, M.I.; Kim, B.H.; Song, C.H. Effects of nutrient solution level and potting media on the growth and flowering of *Cymbidium* Show Girl 'Husky Honey'. *Hortic. Sci. Technol.* **1998**, *16* (Suppl. 1), 124.
8. Lee, Y.R.; Kim, M.S.; Choi, S.R.; Goo, D.H.; Kwon, O.K.; Huh, E.J. Selection of optimum medium and fertilizer yield for export of *Cymbidium*. *Hortic. Sci. Technol.* **2005**, *23* (Suppl. 1), 107.
9. Kwon, A.; Go, J.; Park, S. Effect of autoclaved lightweight concrete (ALC) on growth and flowering in three species of *Cymbidium* and *Doritaenopsis* plants as a potting medium. *J. Agric. Life Sci.* **2015**, *49*, 27–36. [CrossRef]
10. Motomura, H.; Yukawa, T.; Ueno, O.; Kagawa, A. The occurrence of crassulacean acid metabolism in *Cymbidium* (Orchidaceae) and its ecological and evolutionary implications. *J. Plant Res.* **2008**, *121*, 163–177. [CrossRef]
11. Lee, D.S.; Kwon, O.K.; Kim, M.S.; Park, P.M.; Park, P.H.; Lee, Y.R.; An, H.R. Effect of irrigation methods on the growth of *Cymbidium* and saving water for irrigation. *Hortic. Sci. Technol.* **2014**, *32* (Suppl. 2), 166–167.
12. Bayer, A.; Mahbub, I.; Chappell, M.; Ruter, J.; van Iersel, M.W. Water use and growth of *Hibiscus acetosella* 'Panama Red' grown with a soil moisture sensor-controlled irrigation system. *HortScience* **2013**, *48*, 980–987. [CrossRef]
13. Burnett, S.E.; van Iersel, M.W. Morphology and irrigation efficiency of *Gaura lindheimeri* grown with capacitance sensor-controlled irrigation. *HortScience* **2008**, *43*, 1555–1560. [CrossRef]
14. Nam, S.; Kang, S.; Kim, J. Maintaining a constant soil moisture level can enhance the growth and phenolic content of sweet basil better than fluctuating irrigation. *Agric. Water Manag.* **2020**, *238*, 106203. [CrossRef]
15. Pershey, N.A.; Cregg, B.M.; Andresen, J.A.; Fernandez, R.T. Irrigating based on daily water use reduces nursery runoff volume and nutrient load without reducing growth of four conifers. *HortScience* **2015**, *50*, 1553–1561. [CrossRef]
16. van Iersel, M.W.; Dove, S.; Kang, J.-G.; Burnett, S.E. Growth and water use of Petunia as affected by substrate water content and daily light integral. *HortScience* **2010**, *45*, 277–282. [CrossRef]
17. Warsaw, A.L.; Fernandez, R.T.; Cregg, B.M.; Andresen, J.A. Container-grown ornamental plant growth and water runoff nutrient content and volume under four irrigation treatments. *HortScience* **2009**, *44*, 1573–1580. [CrossRef]

18. Chappell, M.; Dove, S.K.; van Iersel, M.W.; Thomas, P.A.; Ruter, J. Implementation of wireless sensor networks for irrigation control in three container nurseries. *HortTechnology* **2013**, *23*, 747–753. [CrossRef]

19. De Boodt, M.; Verdonck, O. The physical properties of the substrates used in horticulture. *Acta Hortic.* **1972**, *26*, 37–44. [CrossRef]

20. Lukanu, G.; Savage, M.J. Calibration of a frequency-domain reflectometer for determining soil-water content in a clay loam soil. *Water* **2007**, *32*, 37–42.

21. Topp, G.C.; Davis, J.L.; Annan, A.P. Electromagnetic determination of soil water content: Measurements in coaxial transmission lines. *Water Resour. Res.* **1980**, *16*, 574–582. [CrossRef]

22. Viets, F.G. Fertilizers and the efficient use of water. In *Advances in Agronomy*; Norman, A.G., Ed.; Academic Press: New York, NY, USA, 1962; Volume 14, pp. 223–264.

23. Lambers, H.; Chapin, F.S.; Pons, T.L. *Plant Physiological Ecology*, 2nd ed.; Springer: New York, NY, USA, 2008; pp. 163–223.

24. Koubouris, G.; Bouranis, D.; Vogiatzis, E.; Nejad, A.R.; Giday, H.; Tsaniklidis, G.; Ligoxigakis, E.K.; Blazakis, K.; Kalaitzis, P.; Fanourakis, D. Leaf area estimation by considering leaf dimensions in olive tree. *Sci. Hortic.* **2018**, *240*, 440–445. [CrossRef]

25. Garland, K.F.; Burnett, S.E.; Day, M.E.; Van Iersel, M.W. Influence of substrate water content and daily light integral on photosynthesis, water use efficiency, and morphology of *Heuchera americana*. *J. Am. Soc. Hortic. Sci.* **2012**, *137*, 57–67. [CrossRef]

26. Ng, C.K.Y.; Hew, C.S. Orchid pseudobulbs—'False' bulbs with a genuine importance in orchid growth and survival! *Sci. Hortic.* **2000**, *83*, 165–172. [CrossRef]

27. Yong, J.W.H.; Hew, C.S. Partitioning of 14^C assimilates between sources and sinks during different growth stages in the sympodial thin-leaved orchid *Oncidium* Goldiana. *Int. J. Plant Sci.* **1995**, *156*, 188–196. [CrossRef]

28. Pan, R.C.; Ye, Q.S.; Hew, C.S. Physiology of *Cymbidium* sinense: A review. *Sci. Hortic.* **1997**, *70*, 123–129.

29. Zheng, X.N.; Wen, Z.Q.; Pan, R.C.; Hew, C.S. Response of *Cymbidium sinense* to drought stress. *J. Hortic. Sci.* **1992**, *67*, 295–299. [CrossRef]

30. Guerfel, M.; Baccouri, O.; Boujnah, D.; Chaïbi, W.; Zarrouk, M. Impacts of water stress on gas exchange, water relations, chlorophyll content and leaf structure in the two main Tunisian olive (*Olea europaea* L.) cultivars. *Sci. Hortic.* **2009**, *119*, 257–263. [CrossRef]

31. Dghim, F.; Abdellaoui, R.; Boukhris, M.; Neffati, M.; Chaieb, M. Physiological and biochemical changes in *Periploca angustifolia* plants under withholding irrigation and rewatering conditions. *S. Afr. J. Bot.* **2018**, *114*, 241–249. [CrossRef]

32. Rhie, Y.H.; Kang, S.; Kim, J. Substrate water content influences the flowering of *Doritaenopsis* Queen Beer 'Mantefon'. *HortScience* **2017**, *52*, 1823–1828. [CrossRef]

33. Currey, C.J.; Flax, N.J.; Litvin, A.G.; Metz, V.C. Substrate volumetric water content controls growth and development of containerized culinary herbs. *Agronomy* **2019**, *9*, 667. [CrossRef]

34. Zhen, S.; Burnett, S.E. Effects of substrate volumetric water content on English Lavender morphology and photosynthesis. *HortScience* **2015**, *50*, 909–915. [CrossRef]

35. Schmidt, G.; Zotz, G. Inherently slow growth in two Caribbean epiphytic species: A demographic approach. *J. Veg. Sci.* **2002**, *13*, 527–534. [CrossRef]

36. Shefferson, R.P. Survival costs of adult dormancy and the confounding influence of size in lady's slipper orchids, genus *Cypripedium*. *Oikos* **2006**, *115*, 253–262. [CrossRef]

37. Ichhashi, S. Orchid production and research in Japan. In *Orchid Biology*; Arditti, J., Pridgeon, A.M., Eds.; Review and Perspectives VII; Kluwer Academic Publishers: Amsterdam, The Netherlands; pp. 171–212.

38. Lopez, R.G.; Runkle, E.S. Temperature and photoperiod regulate flowering of potted *Miltoniopsis* orchids. *HortScience* **2006**, *41*, 593–597. [CrossRef]

39. Zhou, S.; Duursma, R.A.; Medlyn, B.E.; Kelly, J.W.G.; Prentice, I.C. How should we model plant responses to drought? An analysis of stomatal and non-stomatal responses to water stress. *Agric. For. Meteorol.* **2013**, *182*, 204–214. [CrossRef]

40. Kim, J.; Malladi, A.; van Iersel, M.W. Physiological and molecular responses to drought in Petunia: The importance of stress severity. *J. Exp. Bot.* **2012**, *63*, 6335–6345. [CrossRef]

41. He, J.; Norhafis, H.; Qin, L. Responses of green leaves and green pseudobulbs of CAM orchid *Cattleya laeliocattleya* Aloha case to drought stress. *J. Bot.* **2013**, 710539. [CrossRef]

42. Du, T.; Kang, S.; Sun, J.; Zhang, X.; Zhang, J. An improved water use efficiency of cereals under temporal and spatial deficit irrigation in north China. *Agric. Water Manag.* **2010**, *97*, 66–74. [CrossRef]

43. Rafi, Z.N.; Kazemi, F.; Tehranifar, A. Effects of various irrigation regimes on water use efficiency and visual quality of some ornamental herbaceous plants in the field. *Agric. Water Manag.* **2019**, *212*, 78–87. [CrossRef]

44. Giday, H.; Fanourakis, D.; Kjaer, K.H.; Fomsgaard, I.S.; Ottosen, C.O. Threshold response of stomatal closing ability to leaf abscisic acid concentration during growth. *J. Exp. Bot.* **2014**, *65*, 4361–4370. [CrossRef] [PubMed]