A DISSERTATION FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

FDR Sensor Application for Young *Cymbidium* Production with Coir Dust for Efficient Irrigation

심비디움 유식물 코이어 재배 시 효율적 관수를 위한 토양 수분 센서 활용

BY

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FEBRUARY, 2021

MAJOR IN HORTICULTURAL SCIENCE AND BIOTECHNOLOGY
DEPARTMENT OF AGRICULTURE, FORESTRY, AND BIORESOURCES
THE GRADUATE SCHOOL OF SEOUL NATIONAL UNIVERSITY

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UNDER THE DIRECTION OF DR. KI SUN KIM SUBMITTED TO THE FACULTY OF THE GRADUATE SCHOOL OF SEOUL NATIONAL UNIVERSITY

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ABSTRACT

Most orchid growers have used bark as a substrate to avoid over-wet conditions, although it requires excessive water use with leaching. Although bark can provide adequate aeration for orchid growth with its large porosity, it can waste a massive amount of water and fertilizers by leaching. However, most orchid growers are reluctant to change their substrate because of the difficulty in water management of substrates with high water-holding capacity. In addition, the growers irrigate the plants based on their experience, and changing the substrate from bark to others would require growers to adopt a new irrigation method. In this study, a series of experiments were conducted to investigate the applicability of FDR soil moisture sensor-based precision irrigation system for *Cymbidium* production with efficient irrigation management, to compare the various substrates with similar moisture availability conditions, and to find out the optimal substrate volumetric water content

and fertilization rate. In Chapter I, the growth and water use efficiency of *Cymbidium* in various substrates were compared using the precision automated irrigation system. In Chapter II, the growth, photosynthetic activity, and water use efficiency of the plants grown under various substrate volumetric water contents were investigated to determine the optimum volumetric water content for growing young *Cymbidium* plants. In Chapter III, the relationship of growth with fertilization rate was analyzed to figure out the optimum fertilization rate in young *Cymbidium* plants. In Chapter I, pseudobulb size, net photosynthetic assimilation rate, and fresh shoot and root weight of the *Cymbidium* plants were not significantly different among the substrates. The amount of irrigation was significantly lower (1/8) in the coir dust and the commercial growing mix than in bark and coconut husk chips, indicating that fine substrates with higher water-holding capacity could use water more efficiently. Water use efficiency was 8-9.5 times higher in *Cymbidium* grown in fine substrates than those in coarse substrates. In Chapter II, although the net photosynthesis of the plants grown at volumetric water content (θ) threshold of 0.35 $m^3 \cdot m^{-3}$ was also lower than that at 0.55 $m^3 \cdot m^{-3}$, the plants grown at 0.25 $m^3 \cdot m^{-3}$ had significantly lower biomass at harvest than those at the other θ thresholds, suggesting that a critical growth reduction by the water deficit occurred for the plants grown at 0.25 $m^3 \cdot m^{-3}$. Although the 0.25 $m^3 \cdot m^{-3}$ had the highest WUE and substrate EC, they showed significantly reduced growth compared to the other θ thresholds, and thus this was not an adequate θ threshold level for producing quality *Cymbidium*. In Chapter III, the plants grown at ×0.5 fertilization rate had significantly smaller leaves, lead-bulbs,

and shoot biomass than those at the other fertilization rates. Leaf length and width increased quadratically as the fertilization rate increased. Lead-bulbs were also influenced by fertilization rates quadratically; the fertilization rate from ×1.0 improved the lead-bulbs size compared with the other fertilization rates. Net CO_2 assimilation rate and shoot biomass also displayed a similar trend to leaf size. Therefore, ×1.0 fertilization rate was the most efficient fertilization rate to grow young *Cymbidium* when the plants were grown in coir dust substrate using a FDR soil moisture sensor based precision irrigation system. In conclusion, the precision irrigation system could provide an appropriate moisture level for *Cymbidium* grown in fine substrates, avoiding over wet conditions, and produced quality *Cymbidium* with more efficient water and nutrient use than orchids produced in coarse substrates. 0.35 and 0.45 $m^3 \cdot m^{-3}$ θ threshold levels provided appropriate moisture conditions for the production of quality young *Cymbidium* with high water use efficiency. ×1.0 fertilization rate efficiently promoted the growth of young *Cymbidium* plants.

Keywords: controlled-release fertilizer, efficient irrigation, irrigation strategy, growing mixes, nutrient use efficiency, orchids, water use efficiency, soil moisture sensor

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GENERAL INTRODUCTION

Orchid species have specialized root anatomy with a velamen layer that can absorb atmospheric moisture and nutrients, and terrestrial orchids generally require much more moisture than epiphytic orchids (Lee, 2018). In orchid production, most terrestrial orchids can be damaged by overwatering, as overwatering causes root rot and many other diseases such as black rot, bacterial soft rot, and bacterial brown rot (De et al., 2015; Pal et al., 2020). Therefore, the substrate for orchids should provide good aeration as well as an adequate water-holding capacity. Bark is the most common substrate for orchids in many countries, including Korea, Japan, Taiwan, and the United States (Wang and Konow, 2002; Kwon, 2015; Lee, 2018). However, although bark can provide adequate aeration for rhizosphere of orchids with its large porosity, it can waste a massive amount of water and fertilizers by filtering.

Cymbidium species originate from tropical and subtropical Asia and are one of the most popular orchids in the floriculture market because of its variety of flowers sizes, shapes, colors, and longevity the flowers (De et al., 2015; Barman and Naik, 2017). *Cymbidium* requires cultivation periods of ca. 4-5 years to grow from seedling to marketable flowering plants; efficient long-term management is necessary for profitable *Cymbidium* production (Kim et al., 2011). Although most commercial *Cymbidium* (standard type) also classified as terrestrial plants (Lee, 2018), coarse particle substrates as bark are commonly used to avoid overwatering in conventional *Cymbidium* production like other orchid species (De et al., 2015).

Many studies have been conducted to find alternative substrates that can provide adequate water-holding capacity and aeration for *Cymbidium* to enhance water use efficiency without reducing production quality (Mott, 1955; Lee et al., 2014; De et al., 2015). These reports showed that alternative substrates such as carbonized rice husk, sphagnum moss, coconut husk, clay soil, peat moss, sawdust, and various substrate mixes were able to enhance the growth and flowering of *Cymbidium* compared with bark. However, most orchid growers are reluctant to change their substrate because of the difficulty of water management of orchids on substrates with high water-holding capacity. Also, most orchids are irrigated based on grower's experience, and changing the substrate from bark to another would require growers to adopt a new irrigation method. Furthermore, although the effect of substrates on *Cymbidium* growth has been reported in several studies, the moisture levels in the substrates were not clearly described, and this might have affected the results.

Recently developed soil moisture sensor technology has enabled more effective irrigation by precisely providing water for plants when needed. Several sensor-based precision irrigation systems have been developed over the years for efficient irrigation management. Several soil moisture sensors, including tensiometers, gypsum blocks, capacitance as frequency domain reflectometry (FDR), amplitude domain reflectometry, time domain reflectometry, and neutron proves, can directly measure soil moisture (Lea-Cox, 2012). In particular, FDR is suggested as proper soil moisture sensors for automated irrigation system in commercial scale crop production because the sensor has several advantages such as easy maintenance, low costs, and reliability (Jones, 2004; van Iersel et al., 2013). Therefore, FDR sensor-based precision irrigation system has been developed and successfully used for ornamental crops such as *Ocimum basilicum* (Nam et al., 2020), *Hypericum hidcote* (Bacci et al., 2008), and *Hydrangea macrophylla* (Bañón et al., 2019) to enhance crop quality and productivity. Moreover, many growers who have the FDR sensor-based irrigation systems in their nursery could reduce water usage by irrigation from 22 to 83% (Warsaw et al., 2009; van Iersel et al., 2010; Pershey et al., 2015). These systems reduced water use and reduced bacterial infections by favoring the rhizosphere environment for *Gardenia jasminoides* (Chappell et al., 2013). By adopting this FDR sensor-based automated irrigation system in commercial *Cymbidium* cultivation, the production with precision irrigation system could benefit from the provision of favorable conditions for the specialized root of the plants while increasing water use efficiency when grown in fine particle substrates other than bark. However, few studies have examined applying the sensor-based automated irrigation system to commercial *Cymbidium* production.

In potted plant production, controlled-release fertilizer (CRF) is widely used since it can provide plants with appropriate nutrition and minimize runoff by releasing nutrients gradually (Cox, 1993; Broschat and Moore, 2007), which is more efficient nutrient management with less leaching than water-soluble fertilizers (Chen et al., 2001b). Therefore, several studies investigated to improve water and nutrient efficiency in many potted plants such as petunia, basil, dill, parsley, sage, conifers, and lavender by using the soil moisture sensor-based precision irrigation system with CRFs (Alem et al., 2015; Pershey et al., 2015; Zhen and Burnett, 2015; Currey et al., 2019). CRFs are usually applied in *Cymbidium* production because it can supply constant low levels of nutrients that might provide nutrition stability, help minimize leaching, reduce plant damage, and improve the overall fertilizer use efficiency (Park et al., 2018). These practices, the CRF has been commonly used in conventional *Cymbidium* production combined with the low water and nutrient holding capacity of traditional substrates, resulting in about 75% of the water with dissolved fertilizer is lost by leaching (Lee et al., 2014). Since low water and nutrient use efficiency via conventional irrigation management, growers need to consider greater regard toward nutrient use efficiency and retention for their profitable crop production, increasing fertilizer costs. Although precision irrigation can increase water and nutrient use efficiency by reducing leachate, few studies had quantified both water and nutrient use efficiency when precision irrigation system was applied with the CRFs.

Therefore, this study focused on 1) the applicability of FDR soil moisture sensor-based automated irrigation system for *Cymbidium* production with efficient irrigation management via comparison the growth and water use of *Cymbidium* in various substrates with a similar moisture availability condition, 2) determination of suitable substrate water content for growing *Cymbidium* to increase water use efficiency, and 3) finding out the optimum CRF dose to obtain enhanced water and nutrient use for quality *Cymbidium* production. The thesis consists of three chapters with the following topics:

Chapter I: FDR sensor application for *Cymbidium* under various substrate conditions

Chapter II: Efficient water management for young *Cymbidium* grown in coir dust substrate using a precision irrigation system

Chapter III: Efficient fertilization rate for young *Cymbidium* grown in coir dust substrate using a precision irrigation system

LITERATURE REVIEW

Horticultural Characteristics of *Cymbidium*

Orchidaceae is one of the largest and most diverse families of flowering plants, with more than 28,000 accepted species spanning 763 genera (Christenhusz and Byng, 2016). Among the orchids, *Cymbidium* hybrids are the most popular winter and spring blooming terrestrial, epiphytic, lithophytic, and semi-epiphytic orchids originating from tropical and subtropical Asia; covering North Eastern India, China, Japan, Korea, Malaysia, the Philippines, the Borneo islands, and North Australia, usually grown in cooler climates at high elevations (Lopez and Runkle, 2005; De et al., 2015). Thus, *Cymbidium* is commonly transported from production areas in the lowlands to higher elevations during the warm summer in Korea and Japan to prevent reduced growth and flower bud abortion (Ichihashi, 1997).

Various *Cymbidium* varieties which are cool growing and bear large attractive flowers are widely cultivated in the Netherlands, Australia, New Zealand, the United States, and Asian countries, including Korea, Japan, Taiwan, and China (Pal et al., 2020). *Cymbidiums* imported from the Netherlands fetched as much as US$ 11.18 per stem in Singapore, and those imported by Japan from New Zealand fetched US$ 3.33 per stem. As far as the Dutch Auction market is concerned, the cymbidiums fetched the highest value, averaging Euro cents 331 per stem during 2003-2007 (De et al., 2015). In Korea, commercial growers usually export their *Cymbidium* as a cut flower to Japan, the Netherlands, and the United States and potted plants to China.

The mericlones propagated through micro-propagation have commonly been used for commercial production as they are genetically identical and uniform in size (Pal et al., 2020). In general, *Cymbidium* is required for about 3-4 years of a vegetative growth period for flowering from the deflasking (Kim et al., 2011; Pal et al., 2020).

Environmental Requirement for Growth and Flowering of *Cymbidium*

The temperature influences the flowering and flower quality in *Cymbidium*. When *Cymbidium* 'Sazanami' was transferred to the three different temperature regimes as 8-28℃, 15-30℃, and 20-30℃ after flower bud initiation. Their flowering was delayed by 1 month under 8-28℃ and promoted by 1 month under 20-30℃ as compared to 15-30℃ (Li et al., 2001). The high-quality flowers were observed in the moderate temperature regime. However, flower bud abortion at an early stage of flower development was occurred in the highest temperature regime (> 25℃). Therefore, to avoid this disorder, *Cymbidium* growers in Korea and Japan shift their plants from lowland to high elevation regions where the temperature varies between 20 and 30℃ (Ichihashi, 1997). According to Lee and Lee (1993), 30/25, and 25/20℃ (day/night) promoted pseudobulb growth and flower formation in *Cymbidium ensifolium* var. Misericors.

Cymbidiums are affected by temperature and light regardless of their growth stages. *Cymbidium* Lovely Angel 'The Two Virgins' grown under 2℃ without shade produced more lead-bulbs that emerged from primary pseudobulb (mother-bulb), but these were reduced ca. 50% under 50% of shade conditions (Komori and Yoneda, 2002). Although some studies reported that growth and flowering of *Cymbidium* do not affect by photoperiod (Ichihashi, 1997; Dole and Wilkins, 1999; Leonhardt, 2000), night interruption (NI) with low light intensity at 3-7 $\mu mol \cdot m^{-2} \cdot s^{-1}$ for four h (22:00-02:00) could promote flower induction with the increased growth rate during the vegetative stage in *Cymbidium* ‘Red Fire’ and ‘Yokihi’, and high light intensity of NI (120 $\mu mol \cdot m^{-2} \cdot s^{-1}$) produced high-quality flowering in both cultivars (Kim et al., 2011). The researcher reported that increased pseudobulb size by photosynthetic assimilates through NI could promote or accelerate flowering of *Cymbidium* ‘Red Fire’.

Irrigation and Potting Media for Growing *Cymbidium*

Irrigation management is important in growing orchids. Several factors, such as temperature, light conditions, humidity, potting media, pot size, and plant growth condition, can affect irrigation management (Lee, 2018). Terrestrial orchids, including *Cymbidium*, *Cattleya*, *Dendrobium,* usually prefer keeping the potting media slightly moistened at all times(Ichihashi, 1997; De et al., 2015; Lee, 2018). Nevertheless, *Cymbidium* growers commonly use a coarse substrate as bark to avoid diseases such as black rot, crown rot, or heart rot (*Pythium ultimum, P. splendens, Phytophthora palmivora, and P. parasitica*) caused by overwatering (De et al., 2015; Pal et al., 2020).

Although orchids can be grown in a variety of potting media, various substrates, such as bark, coconut husk chips, coir dust, peat moss, charcoal, pumice, aliflor, perlite, sphagnum moss, and other synthetic materials, have different physicochemical properties, such as water and nutrient holding capacity, pH value, and decomposition rate (Richter, 1982; Ichihashi, 1997). Therefore, to choose a potting media for *Cymbidium*, it is important to consider the physical properties that allow the *Cymbidium* to have adequate moisture and nutrients for growth while avoiding overwatering. Sheehan (1997) reported the general requirement of an excellent potting mix; 1) durability, 2) water holding capacity, 3) drainage and aeration, 4) ability to supply nutrients, 5) promote ionic exchange between the water and roots, 6) deter the development of microbes and fungi, and 7) the availability and cost of the substrates. Moreover, the use of the same substrate is an easy way to handle irrigation and fertigation.

Soil Moisture Sensor and Precision Irrigation in Horticulture

Recently developed soil moisture sensor technology has enabled more effective irrigation by precisely providing water for plants when needed. Various soil moisture sensors, including tensiometers, gypsum blocks, capacitance as frequency domain reflectometry (FDR), time domain reflectometry (TDR), amplitude domain reflectometry (ADR), and neutron proves, can directly measure soil moisture (Lea-Cox, 2012). In particular, FDR soil moisture sensors are suggested as suitable soil moisture sensors for the automated irrigation system in greenhouse production because of easy maintenance, low costs, and reliability (Jones, 2004; van Iersel et al., 2013) (Table L-1).

The use of the precision irrigation system improves water and nutrient use efficiency in horticultural crops, such as *Hibiscus acetosella* ‘Panama Red’ (Bayer et al., 2013), *Gaura lindherimeri* (Burnett and Van Iersel, 2008), *Ocimum basilicum* (Nam et al., 2020), *Hypericum hidcote* (Bacci et al., 2008), and *Hydrangea macrophylla* (Bañón et al., 2019). Many growers who have implemented soil moisture sensor-based irrigation systems in their commercial nursery could reduce water usage by irrigation from 22 to 83% (Warsaw et al., 2009; van Iersel et al., 2010; Pershey et al., 2015). These systems reduced water use and reduced pathogen susceptibility by favoring the rhizosphere environment for *Gardenia jasminoides* (Chappell et al., 2013). Thus, if the precision irrigation system based on soil moisture sensors is adopted in commercial *Cymbidium* production, it could be useful for providing favorable conditions for the unique root of *Cymbidium* and increasing water and nutrient use efficiency.

Table L-1. Some methods of measuring soil water (Weil and Brady, 2017)

Method	Measure soil water		Range, kPa	Comments
	Content	Potential		
Gravimetric	○		0 to < –10,000	Destructive sampling; slow (1-2 days) unless microwave used. The standard for calibration.
Neutron scattering	○		0 to < –1,500	Radiation permit needed; expensive equipment; not good in high organic matter soils; requires access tube.
Time domain reflectometry (TDR)	○		0 to < –10,000	Can be automated; accurate to ± 1 to 2% volumetric water content; very sandy, clayey, or salty soils need separate calibration; requires wave guides; expensive instrument.
Frequency domain reflectometry (FDR)	○		0 to < –1,500	Can be automated; accurate to ± 2 to 4% senses volumetric water content; sands or salty soils need special calibration; simple, inexpensive sensors and recording instruments.
Resistance blocks		○	–90 to < –1,500	Can be automated; not sensitive near optimum plant water contents, may need calibration.
Tensiometer		○	0 to –85	Can be automated; accurate to ± 0.1 to 1 kPa; limited range; inexpensive; needs periodic servicing to add water to tensiometer.
Thermocouple psychrometer		○	50 to < –10,000	Moderately expensive; wide range; accurate only to ± 50 kPa.
Pressure membrane apparatus		○	50 to < –10,000	Used with gravimetric method to construct drier part of water characteristic curve.
Tension table		○	0 to –50	Used with gravimetric method to construct wetter part of water characteristic curve.

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CHAPTER I

FDR Sensor Application for *Cymbidium* under Various Substrate Conditions

ABSTRACT

Most orchid growers use bark as a substrate to avoid over-wet conditions, although it requires excessive water use with leaching. This study investigated the applicability of a soil moisture sensor-based automated irrigation system in *Cymbidium* production for efficient irrigation management and compared the growth and water use of *Cymbidium* under various substrate conditions. One-year-old *Cymbidium* 'Hoshino Shizuku' plantlets were grown in pots containing bark, coconut husk chips, coir dust, or a commercial growing mix at a similar matric potential within an easily available water range. Plants were irrigated when the substrate dried below the volumetric water content thresholds at 0.25, 0.30, 0.35, and 0.40 $m^3 \cdot m^{-3}$ for bark, coconut husk chips, coir dust, and the commercial growing mix, respectively. Pseudobulb size, net photosynthetic assimilation rate, and shoot and root fresh weight of the plants were not different among the substrates, although the plants grown in Sunshine Mix4 showed better shoot growth than those in the other substrates. The irrigation amount was significantly higher (7-8 times) in bark and coconut husk chips than in coir dust and Sunshine mix4, indicating that fine substrates with higher water-holding capacity could use water more efficiently. The irrigation amount and electrical conductivity of the substrate in the coarse substrates, bark and coconut husk chips, were much lower than those in the fine substrates, coir dust and commercial growing mix, producing a difference in the growth of the *Cymbidium* among the substrates. Water use efficiency was 8-9.5 times higher in the

plants grown in the fine substrates than those in the coarse substrates. Using FDR sensor-based automated irrigation system, higher quality *Cymbidium* could be produced in the fine substrates with more efficient water and nutrient use than those in the coarse substrates.

INTRODUCTION

In the horticultural industry, orchid species, including *Cattleya*, *Cymbidium*, *Dendrobium*, *Oncidium*, *Paphiopedilum*, and *Phalaenopsis*, have become very popular and important floricultural crops over the last few decades (Lee, 2018). The *Cymbidium* species originate from tropical and subtropical Asia and is one of the most popular orchids in the floriculture market throughout the world because of its variety of flower sizes, shapes, colors, and longevities (Barman and Naik, 2017; De et al., 2015). Since *Cymbidium* generally requires a long cultivation period of ca. 5 years for sale as cut flowers or potted plants in commercial production, they require continuous long-term, and efficient management for production (Kim et al., 2011).

Orchid species have specialized root anatomy with a velamen layer that can absorb atmospheric moisture and nutrients, and terrestrial orchids such as *Cymbidium* generally require much more moisture than epiphytic orchids (Lee, 2018). In commercial orchid production, most terrestrial orchids are commonly damaged by overwatering rather than by underwatering, as overwatering leads to root rot and many other diseases such as black rot, bacterial soft rot, and bacterial brown rot (De et al., 2015; Pal et al., 2020). Therefore, the substrate for orchid production should provide good aeration as well as an adequate water-holding capacity. Bark is the most common substrate for orchid production in many countries, including Korea, Japan, Taiwan, and the United States (Lee, 2018; Kwon et al., 2015; Wang and Konow, 2002). Although bark can provide adequate aeration for orchid species with its large porosity, it can lead to a waste of a massive amount of water and fertilizers by filtering. For example, *Cymbidium* growers in Korea usually irrigate 9,000 L of water per 1 ha everyday during the growing season via overhead sprinklers, and 75% of the water with dissolved fertilizer is leached (Lee et al., 2014).

Alternative substrates that can provide both adequate water-holding capacity and aeration have been searched to enhance water use efficiency without reducing production quality (De et al., 2015; Lee, 1994; Lee et al., 2014; Mott, 1955). Many substrates such as carbonized rice husk, sphagnum moss, coconut husk, clay soil, peat moss, sawdust, and various substrate mixes have been reported to be able to enhance the growth and flowering of *Cymbidium* compared when the plants were grown in bark. However, most orchid growers are reluctant to change their substrate because of the difficulty of water management on substrates with high water-holding capacity. In addition, most orchid growers irrigate plants based on their experience, and changing the substrate from bark to another would require growers to adopt a new irrigation method. Furthermore, although the effect of substrates on *Cymbidium* growth has been reported in several studies, the moisture levels in the substrates were not clearly described.

Sensor-based irrigation technologies have been developed over the years for efficient irrigation management. Various soil moisture sensors, including tensiometers, gypsum blocks, frequency domain reflectometry (FDR), and neutron proves, can directly measure soil moisture (Lea-Cox, 2012). In particular, FDR soil moisture sensors are suggested as suitable soil moisture sensors for the automated irrigation system in nursery and greenhouse production because of easy maintenance, low costs, and reliability (Jones, 2004; van Iersel et al., 2013). Soil moisture sensor-based irrigation has been successfully used for floricultural crops such as *Ocimum basilicum* (Nam et al., 2020), *Hypericum hidcote* (Bacci et al., 2007), and *Hydrangea macrophylla* (Bañón et al., 2019) to enhance crop yield and productivity. However, the sensor-based automated irrigation system has seldom been applied to *Cymbidium* production.

Therefore, we investigated the effect of four substrates (bark, coconut husk chip, coir dust, and a commercial growing mix) on *Cymbidium* growth using a FDR sensor-based automated irrigation system. Irrigation threshold levels for each substrate were designated to consider the moisture retention properties of each substrate to provide a similar level of matric potential. The objectives of this study were 1) to investigate the applicability of a soil moisture sensor-based automated irrigation system for *Cymbidium* production with efficient irrigation management and 2) to compare the growth and water use of *Cymbidium* in various substrates with a similar moisture availability condition.

MATERIALS AND METHODS

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 March 29, 2019. The plants were manually watered for 5 weeks to acclimate them to the experimental greenhouse environment, located in Seoul National University Farm, Suwon, Korea. After washing all the roots, the plants were transplanted in 1,330 ml plastic pots (15 × 13 cm, diameter × height), filled with one of four substrates: pine bark (Hyundae Bark, Gimhae, Korea; originated from China), coconut husk chips (Satis International Co., Ltd., Seoul, Korea; originated from Sri Lanka), coir dust (Satis International Co., Ltd.), and a commercial horticultural growing mix (Sunshine Mix4; Sun Gro Horticulture, Agawam, MA, USA) (Fig. I-1). After transplanting, the plants were placed in the same greenhouse and carefully managed for seven weeks to acclimate them to each substrate for root stabilizing to the new substrates. Plants were fully irrigated on June 21, 2019 and not irrigated until the automated irrigation began on June 26, 2019. When the treatments began, the number of leaves, length and width of the uppermost fully expanded leaf, the number of pseudobulbs, the longest pseudobulb diameter, and chlorophyll content were 16.6 ± 0.31 (mean ± SE, n = 12), 42.9 ± 0.78 cm, 1.9 ± 0.01 cm, 1 ± 0.00, 20.1 ± 0.34 mm, and 53.6 ± 1.60, respectively. The experiment was carried out for 21 weeks, from June 26, 2019 to November 13, 2019.

Fig. I-1. Bark (A), coconut husk chips (B), coir dust (C), and Sunshine Mix4 (D) used for substrates in this study.

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 daily average temperature, relative humidity, vapor pressure deficit, and daily light integral in the greenhouse were 19.9 ± 2.6°C (mean ± SD), 68.6 ± 8.1%, 1.6 ± 0.4 kPa, and 5.2 ± 1.8 mol·m^{-2}·d^{-1}, respectively.

Moisture Retention and Chemical Properties of Substrates

Moisture retention curves of each substrate were investigated to determine the proper irrigation threshold volumetric water content (VWC) level for each substrate using Hyprop (Meter Group, Pullman, WA, USA), following the method described by O'Meara et al. (2014). Each setpoint for irrigation was determined in the range around easily available water (EAW) for soilless media (–1 and –5 kPa suctions; De Boodt and Verdonck, 1972); the determined setpoint for each substrate was described as VWC in Table 1. The chemical properties were analyzed using soil chemical analysis methods (NAAS, 2010). The pH and electrical conductivity (EC) of each substrate were determined by the substrate: distilled water (1:5) method using a pH and EC meter (Orion 3 Star; Thermo Fisher Scientific Inc., Beverly, MA, USA). The contents of exchangeable cations K^+, Na^+, Ca^{2+}, and Mg^{2+} were quantified by atomic absorption spectroscopy (Integra XL, GBC Scientific, Melbourne, Australia). Available P_2O_5 was determined by Lancaster methods, and NO_3^+-N and NH_4^--N were analyzed with Kjeldahl methods. The EC of the substrates at harvest was determined by the Pour Thru extraction method (Wright, 1986).

FDR Soil Moisture Sensor-based Automated Irrigation System

Twelve FDR soil moisture sensors (EC-5; Meter Group) were connected to a data logger (CR1000; Campbell Scientific) to measure and control the VWC in pots. The data logger powered the soil moisture sensors with 2.5 V excitation, and substrate-specific calibration was conducted following the method of Rhie and Kim (2017). Each sensor (5.5 × 1.0 cm, length × width) was inserted diagonally from the top of the substrate in the center 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 twelve solenoid valves (NaanDanJain Irrigation Ltd., Rehovot, Israel). Each experimental unit had five plants as sub-replicates, and the VWC was measured for one pot in the center for each experimental unit every 20 min. If the VWC reading of the capacitance sensors in an experimental unit dropped below the assigned VWC setpoint, the data logger opened the solenoid valve for that experimental unit for 120 s. The plants were irrigated using a sprinkler (Vibro-spreader 35 L/H; Rain-Tal Ltd., Kibbutz Barkai, Israel), and each irrigation event provided ca. 10 mL per pot. The data logger recorded each irrigation application, and the total amount of water applied to the plants was calculated as water use. During the experiment, the plants were provided with a 15N-4.8P-10.8K + 2Mg + Trace elements controlled-release fertilizer (Osmocote Plus; Everris International B.V., Heerlen, The Netherlands) at a rate of 4 g per pot. The fertilizer was employed onto the surface of each substrate when the automated irrigation treatment was initiated.

Plant Growth Parameters and Water Use Efficiency

At the end of the experiment, the total number of leaves, the length and width of the uppermost fully expanded leaf, and the fresh and dry weight of shoots and roots were measured. The pseudobulb diameter was measured at the widest point 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 samples in an oven at 80°C for 7 d. Water use efficiency (WUE) of the plants was calculated as the total dry weight of the plants (in g) divided by the water use amount calculated from the automated irrigation system.

Photosynthetic Gas Exchange

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 17 weeks after the treatment. 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 photosynthetic photon flux density at 1,000 $\mu mol \cdot m^{-2} \cdot s^{-1}$. 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 of gas exchange had been achieved, the net photosynthetic assimilation rate (A_n) was determined.

Experimental Design and Statistical Analysis

The experiments were employed in 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 Tukey's honestly significant difference test at $\alpha = 0.05$ using SAS 9.4 (SAS Institute, Cary, NC, USA). Regression analysis was used for the substrate-specific VWC calibration and to investigate the relationships between EC and the irrigation amount using SigmaPlot (SigmaPlot 11.0, Systat Software Inc., San Jose, CA, USA).

RESULTS AND DISCUSSION

Moisture Retention and Chemical Properties of Substrates

The EAW range (from –1 to –5 kPa suction) of each substrate was measured to determine the proper VWC setpoint for irrigation by analyzing the moisture retention curve using a modular instrument (Hyprop; Meter Group) (Table I-1). Since bark and coconut husk chips had a relatively narrow VWC range (less than 0.05 $m^3 \cdot m^{-3}$) within the EAW (0.22-0.27 and 0.29-0.31 $m^3 \cdot m^{-3}$ for bark and coconut husk chips, respectively), their midpoints were selected as their setpoints. Coir dust and Sunshine Mix4 displayed a wider VWC range (higher than 0.25 $m^3 \cdot m^{-3}$) for EAW (0.34-0.65 and 0.37-0.62 $m^3 \cdot m^{-3}$ for coir dust and Sunshine Mix4, respectively). Since coir dust and Sunshine Mix4 have a much higher water-holding capacity, the set VWC for irrigation with coir dust and Sunshine Mix4 was selected around the –4.5 kPa range to avoid over-wet conditions. VWC setpoints for bark, coconut husk chips, coir dust, and Sunshine Mix4 were determined as 0.25, 0.30, 0.35, and 0.40 $m^3 \cdot m^{-3}$, respectively (Table I-1). Since each substrate has its unique water-retention property, determining VWC setpoints with a similar matric potential level would be beneficial to compare the effect of substrates on plant growth without any drought or waterlogging effects. Based on the properties of capacitance soil moisture sensors, substrates were properly calibrated to measure accurate VWC in pots (Rhie and Kim, 2017). Substrate-specific calibration was conducted to measure the VWC accurately, and the calibration coefficients are listed in Table I-1.

Coconut husk chips had the highest pH at 5.8, and the pH of bark was higher than that of coir dust or Sunshine Mix4 (Table I-2). However, the pH range of all the substrates was within the optimum range for orchid growth, which is between 5.0 and 6.5 (De et al., 2015). EC levels were also significantly different among the substrates, with the highest EC in coconut husk chips (0.83 $dS \cdot m^{-1}$), followed by coir dust (0.74 $dS \cdot m^{-1}$), Sunshine Mix4 (0.46 $dS \cdot m^{-1}$), and bark (0.16 $dS \cdot m^{-1}$). Although Sunshine Mix4 had a lower EC than coconut husk chips and coir dust, it had significantly higher N, K, and Mg contents than any other substrates, indicating the acceptable range of nutrients for a plant-growing substrate (Table I-2). The high EC of coconut-based substrates (coconut husk chips and coir dust) was mostly due to significantly high K and Na. Lee (2018) reported that the coconut-based substrate must be thoroughly washed to eliminate any salts before use because coconut trees usually grow near the seashore. Thus, the coconut-based substrates used in this study were washed thoroughly to avoid high sodium levels. The EC level of substrates was not severe and allowed *Cymbidium* growth without salt accumulation during the experimental period (Pal et al., 2020). Since the bark has been aged and carbonized for months, EC, and most nutrients in the bark were the lowest among all the substrates; calcium content was highest in the bark. To avoid nutrient deficiency in substrates for *Cymbidium*, controlled-release fertilizer was provided as described in materials and methods.

Table I-1. Volumetric water content (VWC), the setpoint of VWC, and calibration coefficients for the substrates used in this study.

Substrate	VWC[z] ($m^3 \cdot m^{-3}$)	VWC setpoint ($m^3 \cdot m^{-3}$)	Calibration coefficient[y]		r^2
			α	β	
Bark	0.22-0.27	0.25	0.001	– 0.388	0.93
Coconut husk chips	0.29-0.31	0.30	0.002	– 0.537	0.90
Coir dust	0.34-0.65	0.35	0.002	– 0.545	0.89
Sunshine Mix4	0.37-0.62	0.40	0.002	– 0.750	0.92

[z] Volumetric water content of easily available water (1-5 kPa suction)

[y] Substrate-specific EC-5 sensor calibration coefficients for the formula VWC = $\alpha \times$ sensor output (mV) + β.

Table I-2. Chemical properties of the substrates used in this study.

Substrate	pH	EC ($dS \cdot m^{-2}$)	P_2O_5 ($mg \cdot kg^{-1}$)	Exchangeable cation ($cmol_c \cdot kg^{-1}$)				NO_3^+-N ($mg \cdot kg$)	NH_4^--N ($mg \cdot kg$)
				K	Ca	Mg	Na		
Bark	5.53 b[z]	0.16 d	10.67 d	0.26 c	5.20 a	0.59 c	0.13 c	8.09 b	2.33 b
Coconut husk chips	5.83 a	0.83 a	18.00 c	4.16 a	0.53 c	0.84 b	1.16 a	9.17 b	0.75 c
Coir dust	5.10 c	0.74 b	24.00 b	2.79 b	0.57 c	0.72 bc	1.16 a	9.17 b	2.47 b
Sunshine Mix4	5.17 c	0.46 c	54.33 a	0.28 c	3.67 b	3.53 a	0.30 b	47.1 a	5.20 a

[z]Means within columns followed by the same letters are not significantly different by Tukey's honestly significant difference test at $P \leq 0.05$.

Performance of Precision Automated Irrigation System

Generally, the automated irrigation system was performed as programmed in the data logger (Fig. I-1). Although bark and coconut husk chip reached their set VWC as soon as the treatment started, coir dust and Sunshine Mix4 did not receive their first automated irrigation for 14 d after treatment was initiated. As bark and coconut husk chips are coarse particles with high porosity, water filtration in these substrates was relatively fast, and their VWC reached the set VWC immediately after treatment started. However, coir dust and Sunshine Mix4 are peat-based substrates with much higher water-holding capacity (Arguedas et al., 2007; Raviv and Lieth, 2008), yet providing plants with water within the EAW range for 14 days. Although there were missing data for a few days from a technical issue with the automated irrigation system caused by an electrical outage at the greenhouse, the soil moisture sensor-based automated irrigation could maintain the VWC of the substrates according to the set VWC threshold as scheduled throughout the experimental period of 21 weeks (Fig. I-2).

Growth of *Cymbidium*

Cymbidium grown in Sunshine Mix4 had the highest number of leaves than those in the other substrates; no significant differences were observed in the number of leaves among those in bark, coconut husk chips, and coir dust (Table I-3). Leaf width and length were also highest in *Cymbidium* grown in Sunshine Mix4, but the differences were not significant from those in coir dust. Plants grown in bark and

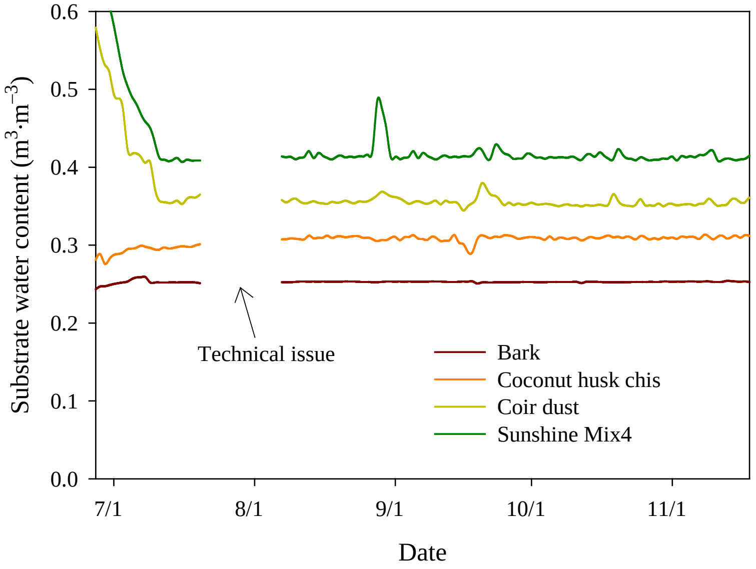

Fig. I-2. Substrate water content ($m^3 \cdot m^{-3}$) changes of bark, coconut husk chips, coir dust, and Sunshine Mix4 during *Cymbidium* 'Hoshino Shizuku' cultivation using a sensor-based automated irrigation system. Setpoints were designated at 0.25, 0.30, 0.35, and 0.40 $m^3 \cdot m^{-3}$ for bark, coconut husk chip, coir dust, and Sunshine Mix4, respectively (n = 3).

coconut husk chips had relatively less and smaller leaf growth, although the substrate matric potential was similar among the substrates. Chlorophyll content also showed similar trends to leaf parameters, with the highest chlorophyll content in *Cymbidium* grown in Sunshine Mix4. Pseudobulb size is generally regarded as a major factor for measuring the growth of *Cymbidium* because pseudobulb is an important to store photosynthetic assimilates from leaves during the vegetative period (Ng and Hew, 2000; Yong and Hew, 1995). In the present study, the pseudobulb was matured, and pseudobulb size was not different among the substrates. Overall, the shoot growth was higher in fine substrates (coir dust and Sunshine Mix4) than in coarse substrates (bark and coconut husk chips), but the difference was not significant.

In contrast to the shoot growth, the root length was significantly shorter in plants grown in coir dust than in those in other substrates (Table I-2, Fig. I-3). Ichihashi (1997) reported that soggy conditions cause diseases such as root rot in orchids, but the diseases were not observed during the present study. Aeration is also an important factor for orchid roots and must be ensured during watering. Sunshine Mix4, which contains perlite, is more porous than coir dust. Thus, aeration through the air space of substrates might affect the root growth of the plants. There was no significant difference in A_n among the substrates ($P = 0.3$) (Fig. I-4). The values of A_n in the present study were within a similar range in the previous study (Kim et al., 2013), indicating that the similar matric potential among the substrates did not affect the photosynthetic activity of the plants. which was relatively lower than those of other C_3 plants (Pan et al., 1994). Consistent with the photosynthetic data, shoot and

Table I-3. Growth of *Cymbidium* 'Hoshino Shizuku' grown in bark, coconut husk chips, coir dust, and Sunshine Mix4 substrates using a sensor-based irrigation system for 21 weeks as influenced by different substrates.

Substrate	No. of leaves	Leaf length (cm)	Leaf width (cm)	Chlorophyll content (SPAD)	Pseudobulb[z] diameter (mm)	Root length (cm)	Fresh weight (g)		Dry weight (g)	
							Shoot	Root	Shoot	Root
Bark	15.2 b[y]	45.4 c	1.93 bc	53.7 bc	37.7	46.8 a	29.3	99.1	9.0 b	7.4
Coconut husk chips	15.3 b	45.8 bc	1.92 c	52.6 c	37.2	41.0 a	30.1	103.3	9.1 b	7.7
Coir dust	16.2 b	49.9 ab	2.05 ab	58.2 ab	38.8	31.1 b	29.7	96.5	9.5 b	6.9
Sunshine Mix4	17.9 a	53.0 a	2.07 a	62.1 a	39.4	40.9 a	32.6	84.5	12.1 a	7.5

[z] Primary pseudobulb was the first formed pseudobulb after deflasking.

[y] Means within columns with a different letter are significantly different by Tukey's honestly significant difference test at $P = 0.05$

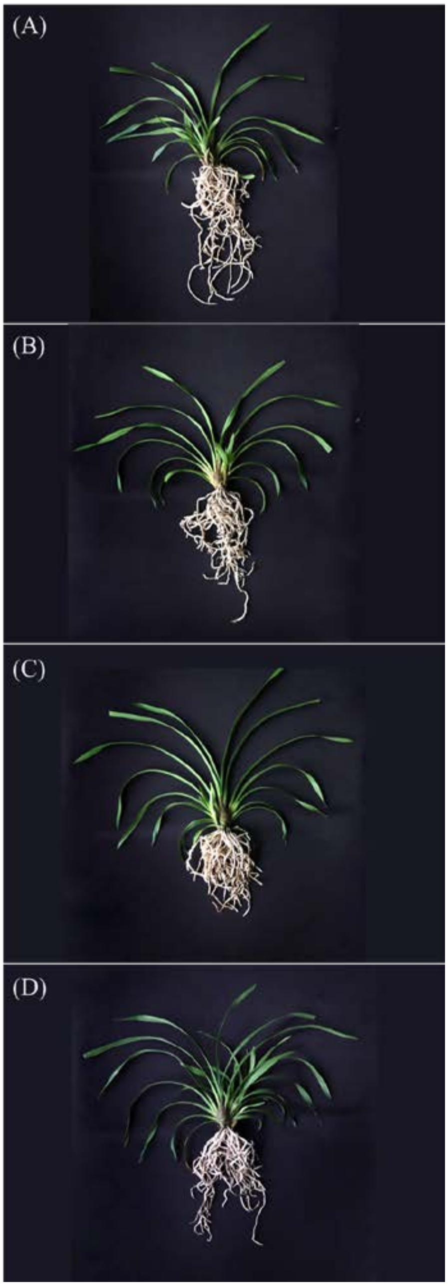

Fig. I-3. Growth of *Cymbidium* ‘Hoshino Shizuku’ grown in the bark (A), coconut husk chips (B), coir dust (C), and Sunshine Mix4 (D) using a sensor-based automated irrigation system. The photographs were taken at harvest after 21 weeks of cultivation.

root fresh weights of *Cymbidium* were not significantly different among the substrates (Table I-3). Although the root dry weights were not significantly different among the substrates, the dry shoot weights of the plants grown in Sunshine Mix4 was higher than those in the other substrates. The highest shoot dry weight in Sunshine Mix4 was consistent with the results of the highest number of leaves, leaf size, and chlorophyll contents in the same substrate.

Pun (2018) reported that *C. etythrostylum* grown in bark had the lowest shoot growth, including pseudobulbs, compared to those grown in the other substrates. Pumice (Kwon, 2015) and the mixture of bark and hydrophilic polymer at 1:1 ratio (Yamane and Sakuramoto, 1992) were also recommended to improve the growth and flowering of *Cymbidium* compared with bark as the substrate; these findings are not consistent with the present results showing no difference in shoot growth among plants in the bark, coconut husk chips, and coir dust substrates. This contradiction might be from different stages of the plantlets or other environmental conditions. Also, different substrate moisture conditions among the substrates might have affected the results. In the present study, bark, coconut husk chips, and coir dust

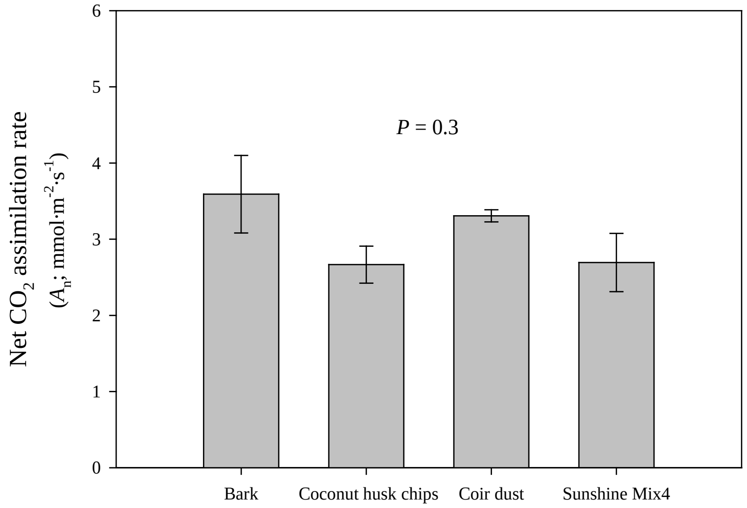

Fig. I-4. Net carbon dioxide assimilation rate (A_n) in the uppermost mature leaf of *Cymbidium* 'Hoshino Shizuku' after 17 weeks of cultivation. The plants were grown in the bark, coconut husk chips, coir dust, and Sunshine Mix4 with volumetric water content at 0.25, 0.30, 0.35, and 0.40 $m^3 \cdot m^{-3}$, respectively. Bars represent the standard errors of the means (n = 3).

showed similar shoot growth of *Cymbidium* at similar substrate matric potential.

Water Use and EC

The total amount of irrigation was significantly higher in the coarse substrates than the fine substrates (Table I-4). Bark and coconut husk chips required 7-8 times more water to retain the substrate-specific set VWC than Sunshine Mix4 during the experiments. Since the bark and coconut husk chips are coarse substrates and had a narrow EAW range (0.05 and 0.03 $m^3 \cdot m^{-3}$ for bark and coconut husk chips, respectively, Table I-1), these substrates were irrigated more frequently to replenish the water that was absorbed by the plants and mostly lost by leaching to maintain the EAW range. However, the fine substrates had higher water-holding capacity with wider EAW range (0.31 and 0.25 $m^3 \cdot m^{-3}$ for coir dust and Sunshine Mix4, respectively, Table I-1), and they could hold the irrigated water more tightly thus required less frequent irrigation than the coarse substrates.

At harvest, the EC values of the substrates were a significantly different between the coarse and the fine substrates. Bark and coconut husk chips had an EC at 0.06 and 0.11 $dS \cdot m^{-1}$ at harvest, which were lower than their initial EC (0.16 and 0.83 $dS \cdot m^{-1}$ for bark and coconut husk chips, respectively), suggesting that extensive irrigation for the coarse substrates leaches the fertilizer, thus the lowering EC. In contrast, the fine substrates increased EC of coir dust and Sunshine Mix4 from the initial EC to 0.74 and 0.46 $dS \cdot m^{-1}$, respectively, (Table I-1), indicating their effective nutrient-holding capacity with less leaching of fertilizer. Thus, the superior

Table I-4. The total amount of irrigation, EC, and water use efficiency (WUE) of *Cymbidium* 'Hoshino Shizuku' grown in the bark, coconut husk chips, coir dust, and Sunshine Mix4 substrates for 21 weeks using a sensor-based automated irrigation system.

Substrates	Total amount of irrigation (L/pot)	EC[z] at harvest ($dS \cdot m^{-1}$)	WUE[y] ($g \cdot L^{-1}$)
Bark	25.9 a[x]	0.06 b	0.70 b
Coconut husk chips	21.9 a	0.11 b	0.77 b
Coir dust	4.6 b	1.32 a	4.11 ab
Sunshine Mix4	3.1 b	1.77 a	6.63 a

[z] Electrical conductivity of each substrate was measured from leachates using Pour Thru extraction at harvest.

[y] Water use efficiency = total dry weight (g) / total amount irrigation (L)

[x] Means within columns followed by the same letters are not significantly different by Tukey's honestly significant difference test at $P = 0.05$.

growth of *Cymbidium* grown in Sunshine Mix4 could be attributed to the higher EC in the substrate than in the other substrates, which is consistent with previous finding (Naik et al., 2013). Based on growth and water use, the WUE was highest in the *Cymbidium* grown in Sunshine Mix4, where it was about 9.5 times higher than those in the coarse substrates (Table I-4).

A regression analysis showed a negative correlation between the amount of water and the substrate EC (Fig. I-5), indicating that extensive irrigation for coarse substrates would require more fertilization (Balman and Naik, 2017). As the water-holding capacity and nutrient-holding capacity are closely related to the particle surface size of the substrate, the substrates with a small particle surface (i.e., bark) had lower water- and nutrient-holding capacities, thus allowing more leaching of nutrients (Jahromi et al., 2018).

Conclusion

This study showed that the sensor-based automated irrigation system successfully produced *Cymbidium* regardless of the substrate. The coarse substrates required about eight times more water than the fine substrates to maintain a similar matric potential, but the plants in various substrates showed similar growth, except for those grown in Sunshine Mix4. These results were not consistent with previous observations that the low growth of *Cymbidium* in bark. The differences between the present and previous results might be the substrate moisture conditions differed from the tested substrates. Nevertheless, the bark was not optimal substrate for

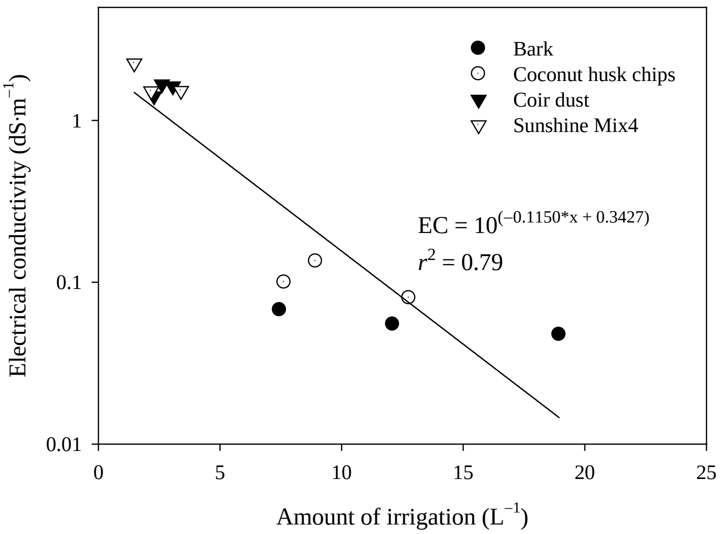

Fig. I-5. Relationships between electrical conductivity and the amount of irrigation in the various substrates. The regression line indicates significant relationships between EC and irrigation amount at the end of the experiment. The *Cymbidium* ‘Hoshino Shizuku’ was provided with 4 g of controlled-release fertilizer.

Cymbidium since it was water and nutrient inefficient compared with the fine substrates. Fine substrates provided many benefits for water- and nutrient-holding capacities, increasing water and nutrient efficiency. As orchid species require enough aeration due to their specialized root system, growers have been reluctant to use fine substrates because of irrigation management difficulty. However, the present results showed that the FDR soil moisture sensor-based automated irrigation system could successfully produce *Cymbidium* with fine substrates with more efficient irrigation than the conventional way. These results will help to reduce labor and production costs and contribute to sustainable orchid production with efficient water and nutrient use.

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CHAPTER II

Efficient Water Management for Young *Cymbidium* Grown in Coir Dust Substrate Using a Precision Irrigation System

The research described in this chapter has been published in

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ABSTRACT

Efficient long-term management for high-quality *Cymbidium* production 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 an FDR 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 (θ) thresholds (0.25, 0.35, 0.45, and 0.55 $m^3 \cdot m^{-3}$). The numbers of leaves and pseudobulbs at harvest, and the chlorophyll content did not differ among the four θ thresholds. However, plants grown at 0.25 $m^3 \cdot m^{-3}$ had significantly smaller leaves, pseudobulbs, and biomass than those at the other θ thresholds. 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 by drought. Although the net photosynthesis at θ of 0.35 $m^3 \cdot m^{-3}$ was also lower than that at 0.55 $m^3 \cdot m^{-3}$, biomass was significantly lower only at 0.25 $m^3 \cdot m^{-3}$ than at the other θ thresholds, suggesting that a critical growth reduction by the water deficit occurred for the plants at 0.25 $m^3 \cdot m^{-3}$. As the θ threshold increased, the total irrigation amount significantly increased, which inversely decreased WUE. Although θ of 0.25 $m^3 \cdot m^{-3}$

showed the highest WUE and substrate EC, the plants grown at 0.25 $m^3 \cdot m^{-3}$ had significantly reduced growth compared to the other θ thresholds, and thus this was not a reliable θ threshold level for producing high-quality *Cymbidium*. Overall, the 0.35 and 0.45 $m^3 \cdot m^{-3}$ thresholds provided appropriate moisture levels for the quality young *Cymbidium* production with high WUE.

INTRODUCTION

Orchids are one of the most commercial floricultural crops and are distributed throughout the world. In the international flower trade, orchids rank sixth among the top ten cut flowers, while *Cymbidium* spp. ranks first among the orchid species (De et al., 2020). Although the price of orchids has been lowered due to technological advances in micro-propagation, 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 (Kim et al., 2011).

Cymbidium have been attempted to be improved flowering and quality of *Cymbidium* by controlling environmental factors such as temperature, light intensity, photoperiod, substrate, and nutrient (Barman et al., 2017; Ohno and Kako, 1978; Pun, 2019) to allow more efficient *Cymbidium* production practice. Bark, which provides macro-pores, is commonly used in commercial production of *Cymbidium* having specialized root structure with a velamen layer susceptible to high moisture conditions. Most *Cymbidium* growers have used bark as substrate to avoid over wet conditions, thus preventing rhizosphere diseases, including root rot, black rot, or bacterial infections. However, this substrate, which has a low water-holding capacity, requires more frequent irrigation with a huge drainage fraction (Hason et al., 2004). Alternative substrate with high water-holding capacity have been investigated to enhance water and nutrient use efficiency. *Cymbidium* growth was observed to be better in carbonized rice hull (Won et al., 1998), peat moss (Lee et al., 2005), and Hyuga pumice (Kwon et al., 2015) than those in 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. 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 during every irrigation (Lee et al., 2014).

Recently developed soil moisture sensor technology has enabled more effective irrigation by precisely providing water for plants when needed, thus improving WUE and nutrient use efficiency in horticultural crops, such as *Hibiscus acetosella* ‘Panama Red’ (Bayer et al., 2013), *Gaura lindherimeri* (Burnett and van Iersel, 2008), and *Ocimum basilicum* (Nam et al., 2020). Many growers who have implemented soil moisture sensor-based irrigation systems in their commercial nursery could reduce water usage by irrigation from 22 to 83% (Pershey et al., 2015; van Iersel et al., 2010; Warsaw et al., 2009). These systems reduce water use and reduce pathogen susceptibility by favoring the rhizosphere environment for *Gardenia jasminoides* (Chappell et al., 2013). By adopting FDR soil moisture sensor-based automated irrigation system in *Cymbidium* production, favorable conditions could be provided for the specialized root of the plants while increasing 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.

MATERIALS AND METHODS

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 March 29, 2019. The plants were manually watered for 5 weeks to acclimate them to the experimental greenhouse environment, located in Seoul National University Farm, Suwon, Korea. After washing off the roots, the plants were transplanted in 1,330 mL plastic pots (15 × 13 cm, diameter × 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 June 29, 2019 and were then not irrigated until the automated irrigation began on July 3, 2019. During the experiment, plants were provided with a 15N-4.8P-10.8K + 2Mg + trace elements controlled-release fertilizer (Osmocote Plus; Everris International B.V., Heerlen, The Netherlands) at 4 g per plant. The fertilizer was applied to the surface of each substrate when automated irrigation treatment was initiated.

When the treatments began on June 29, 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 June 29, 2019 to April 17, 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.

Physicochemical Properties of Coir Dust 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 (VWC, θ) level for the coir dust used in the present experiment (Fig. II-1). Each VWC threshold setpoint 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 (De Boodt and Verdonck, 1972), and the setpoint for irrigation θ thresholds were determined as 0.25, 0.35, 0.45, 0.55 m^3·m^{-3}, which are –15.0, –5.0, –2.6, –1.6 kPa respectively (Fig. II-1). Because *Cymbidium* must avoid wet substrate conditions, which can cause root rot diseases, we set the θ thresholds from the bottom of the available water content.

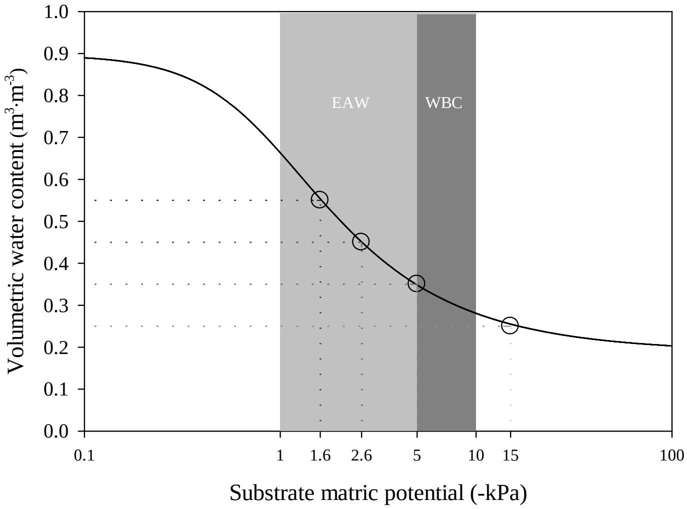

Fig. II-1. Moisture retention curve of the coir dust substrate used in this study. The irrigation θ thresholds were set at −1.6, −2.6, −5.0, and −15.0 kPa, representing water contents of 0.55, 0.45, 0.35, and 0.25 $m^3 \cdot m^{-3}$, respectively, within range of easily available water (EAW) and water buffering capacity (WBC). Each point indicates the relationship between setpoints and substrate matric potential.

Precision Automated Irrigation System

To measure and control the θ in the pots, twelve frequency domain reflectometry (FDR) soil moisture sensors (EC-5; Meter Group) were connected to a data logger (CR1000; Campbell Scientific). The data logger powered the soil moisture sensors with 2.5 V excitation, and substrate-specific calibration was conducted according to the equation; $\theta = 0.1667 \times$ sensor output (mV) – 54.446 ($r^2 = 0.89$). Each sensor was inserted diagonally from the top of the substrate in the center of a pot where the roots were located. The data logger was connected to a relay driver (SDM-CD16AC; Campbell Scientific), which controlled the power to twelve solenoid valves (NaanDanJain Irrigation Ltd., Rehovot, Israel). Each experimental unit had five plants as sub-replicates, and the VWC was measured for one pot in the center for each experimental unit. Every 20 min, if the θ reading of FDR soil moisture 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. Plants were irrigated using spray stakes (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. The data logger recorded each irrigation application, and the daily and total amount of water applied to the plants were subsequently calculated.

Plant Growth Parameters and Water Use Efficiency

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 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.

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 1 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 1,000 $\mu mol \cdot m^{-2} \cdot s^{-1}$. 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 for 1 week. Three plants were measured in each treatment. The uppermost fully expanded leaves were chosen for measurement to avoid the central 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. 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 F_v/F_m was $F_v/F_m = (F_m - F_o)/F_m$.

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 $\alpha = 0.05$, using SAS 9.4 (SAS Institute, Cary, NC, USA). Regression analysis was used for the substrate-specific VWC calibration and investigated the relationships between electrical conductivity and θ thresholds using SigmaPlot (SigmaPlot 11.0, Systat Software Inc., San Jose, CA, USA).

RESULTS AND DISCUSSION

Performance of Precision Automated Irrigation System

The FDR sensor-based precision automated irrigation system properly maintained the θ of the treatments as planned for 42 weeks (Fig. II-2). Although the lower θ thresholds (0.25 and 0.35 $m^3 \cdot m^{-3}$) decreased θ gradually without irrigation for 1 week after the automated irrigation system was initiated, all of the treatments were irrigated when θ dropped below the designated θ thresholds. 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 thresholds, respectively. These standard deviation values were somewhat larger than the previous study, where standard deviation was less than 0.01 $m^3 \cdot m^{-3}$ (Nam et al., 2020); this is mostly due to the use of the spray stake irrigation method used in the present study. However, the automated irrigation system provided a reliable θ thresholds to quantify the effect of θs on *Cymbidium* growth and water use grown in coir dust substrate.

Vegetative Growth of *Cymbidium*

Over 42 weeks of *Cymbidium* growth with the four different θ thresholds, only plants grown at 0.25 $m^3 \cdot m^{-3}$ θ threshold showed relatively smaller leaves and

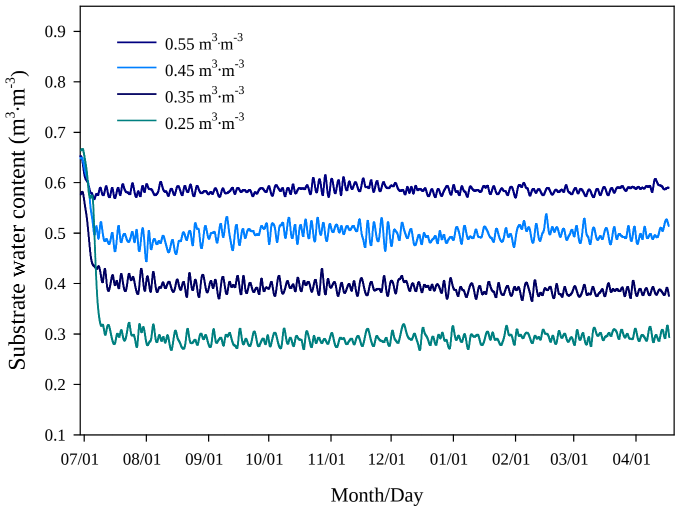

Fig. II-2. Substrate volumetric water content of 1-year-old *Cymbidium* 'Hoshino Shizuku' as maintained by a precision irrigation system for 42 weeks. Plants were irrigated when the substrate water content reading of the FDR sensors dropped below each 0.25, 0.35, 0.45, and 0.55 θ thresholds ($m^3·m^{-3}$).

pseudobulbs than those at higher θ thresholds, but the numbers of leaves and pseudobulb, and chlorophyll contents were similar regardless of the θ thresholds (Table II-1 and Fig. II-3). The leaf size (length and width) of the plants was significantly smaller at 0.25 $m^3 \cdot m^{-3}$ than those at 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 (Lambers et al., 1998). Several ornamental crops, such as *Heuchera americana*, *Gaura lindheimeri*, and petunia, showed a similar tendency, with smaller leaf areas when exposed to drought conditions (Burnett and van Iersel, 2008; Garland et al., 2012; Van Iersel et al., 2010). The pseudobulb is an essential and specialized organ of several orchid species used to store photosynthetic assimilates and water, thus producing a series of adjacent shoots that continue to grow until they bloom (Ng and Hew, 2000; Yong and Hew, 1995). In addition, stored water in pseudobulbs can help *Cymbidium* tolerate drought stress (Pan et al., 1997; Zheng et al., 1992). Although the plants grown at 0.25 $m^3 \cdot m^{-3}$ θ threshold produced a similar number of pseudobulbs, these pseudobulbs were significantly smaller than those from plants grown at the other θ thresholds, indicating that the 0.25 $m^3 \cdot m^{-3}$ mimicked water deficit conditions and thus reduced pseudobulb growth. Although a decline in chlorophyll content at drought conditions has often been reported for several species, such as *Olea europaea*, *Periploca angustifolia*, and *Doritaenosis* (Dghim et al., 2018; Guerfei et al., 2009; Rhie et al

Table II-1. Vegetative growth characteristics of 1 -year-old *Cymbidium* 'Hoshino Shizuku' with a precision irrigation system for 42 weeks as influenced by different substrate volumetric water content (θ) thresholds ($m^3 \cdot m^{-3}$).

θ threshold ($m^3 \cdot m^{-3}$)	No. of leaves	Leaf length (cm)	Leaf width (cm)	No. of pseudobulbs	Pseudobulb^z diameter (mm)	Chlorophyll content
0.55	24.3	48.4 a	2.38 a	2.2	34.2 ab	58.1
0.45	23.6	48.2 a	2.34 ab	2.1	35.8 a	55.8
0.35	25.2	45.8 ab	2.23 bc	2.4	34.0 ab	55.4
0.25	22.0	45.1 b	2.16 c	2.3	31.7 b	58.7

^{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 $\alpha = 0.05$.

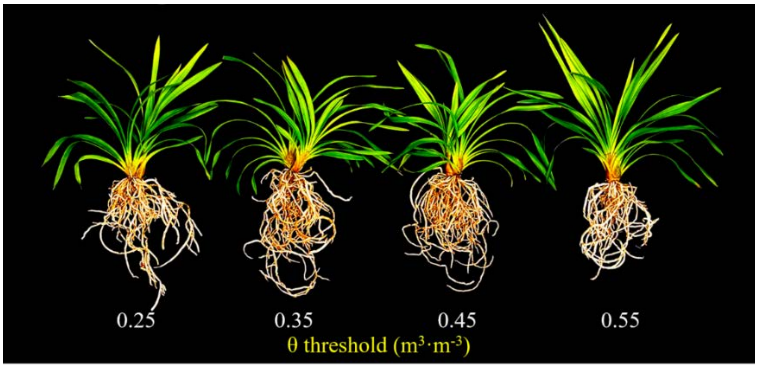

Fig. II-3. Growth of 1-year-old *Cymbidium* ‘Hoshino Shizuku’ grown at 0.25, 0.35, 0.45, and 0.55 θ thresholds ($m^3 \cdot m^{-3}$) using precision automated irrigation system at harvest after 42 weeks of cultivation.

., 2017), *Cymbidium* grown at various θs displayed similar chlorophyll content values for 42 weeks, regardless of the θ thresholds. Likewise, Zheng et al. (1992) reported that 1-year-old leaves of *Cymbidium* did not change their chlorophyll content at 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.

As the lower θ threshold reduced the leaf and pseudobulb size of *Cymbidium*, the θ thresholds affected the fresh and dry weights of pseudobulbs, shoots, and roots of the plants (Table II-2). Among the θ thresholds, all biomass parameters were the lowest at 0.25 $m^3 \cdot m^{-3}$, indicating the detrimental effect of drought. In particular, plants grown at 0.25 $m^3 \cdot m^{-3}$ θ threshold had significantly lower fresh and dry shoot weights, displaying 15 and 5% lower fresh and dry shoot weights than those at the other θ thresholds, respectively, whereas the plants grown at the higher θ thresholds all had similar values. In addition, the fresh and dry weights of pseudobulbs and roots of *Cymbidium* grown at 0.25 $m^3 \cdot m^{-3}$ 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 $m^3 \cdot m^{-3}$, whereas higher θ threshold treatments showed similar biomass values. Currey et al. (2019) reported that parsley, basil, and dill decreased their biomass linearly when they received θ from 0.45 $m^3 \cdot m^{-3}$ to 0.15 $m^3 \cdot m^{-3}$, and Nam et al. (2020) reported that basil grown at 0.45 $m^3 \cdot m^{-3}$ even had

Table II-2. The fresh or dry weight of 1-year-old *Cymbidium* 'Hoshino Shizuku' 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	15.5 ab[y]	110.7 a	133.4 ab	3.4 a	37.1 a	29.6 a
0.45	17.2 a	105.9 a	139.0 a	3.6 a	35.9 a	29.8 a
0.35	14.9 ab	101.1 a	136.6 ab	3.2 ab	35.0 a	29.7 a
0.25	12.5 b	90.0 b	120.1 b	2.6 b	32.7 b	28.2 b

[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 $\alpha = 0.05$.

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 $m^3 \cdot m^{-3}$ (Burnett and van Iersel, 2008; Garland et al., 2012; Zhen and Burnett, 2015). In the present study, 0.25 $m^3 \cdot m^{-3}$ treatment only displayed significantly 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 biomass reduction compared to those grown at higher θ threshold treatments.

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 VWC of 0.1 $m^3 \cdot m^{-3}$, was 57% lower than that at 0.4 $m^3 \cdot m^{-3}$ for 54 d treatment (Zhen et al., 2015). Currey et al. (2019) 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 (Schmidt and Zotz, 2002; Shefferson, 2006). 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* among 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 critical during the young orchid cultivation period, as the pseudobulb size is positively related to flowering quality in orchids, including *Cymbidium*, *Dendrobium*, and *Miltoniopsis* (Kim et al., 2011; Ichhashi, 1997; Lopez and Runkle, 2006).

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 fewer photosynthetic parameters (A_n, g_s, and E) of *Cymbidium* (Fig. II-4, $p < 0.001$). All photosynthetic parameters of the plants grown at 0.25 $m^3 \cdot m^{-3}$ were the lowest among the θ threshold treatments, showing that limited substrate moisture restricted the stomata, thus reducing photosynthesis. The photosynthetic parameters of the plants 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 (Nam et al., 2020; Currey et al., 2019; Zhou et al., 2013). In addition, in other orchid species, the lower θ gradually decreased A_n,

g_s, and E of *Doritaenopsis* 'Mantefon' with the θ threshold decreasing from 0.5 to 0.2 $m^3 \cdot m^{-3}$ (Rhie et al., 2017).

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 among the θ threshold treatments (Fig. II-4, D), 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. (2012) 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, 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 water-storing pseudobulb (Pan et al., 1997; Motomura et al., 2008). The pseudobulb serves as a buffer against drought stress because of its ability to retain water (Ng and Hew, 2000). For example, the water contents of the leaf, root, and pseudobulb remained at 63-70% for 42 d of drought conditions in *Cymbidium*

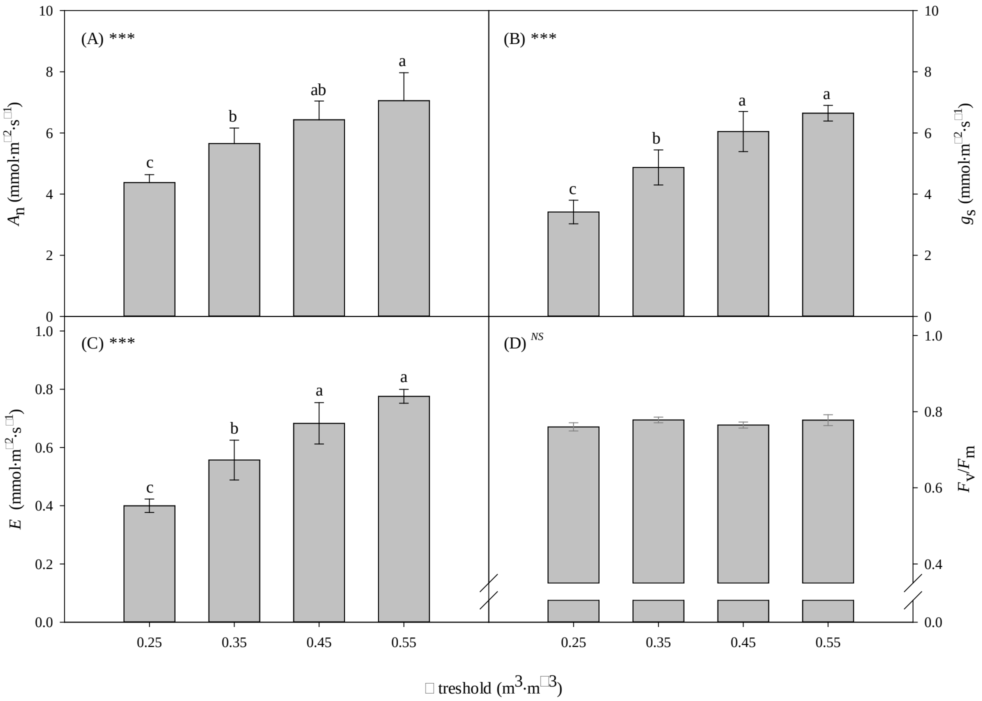

Fig. II-4. Net CO_2 assimilation rate (A_n, A), stomatal conductance (g_s, B), transpiration rate (E, C), and maximum quantum efficiency of photosystem II (F_v/F_m, D) in the uppermost mature leaves of 1-year-old *Cymbidium* 'Hoshino Shizuku' after 41 weeks under 0.25, 0.35, 0.45, and 0.55 θ thresholds ($m^3 \cdot m^{-3}$). Mean separation by Duncan's multiple range test at α = 0.05. Bars present the standard errors of the means (n = 9).

(Zheng et al., 1992). He et al. (2013) also reported that pseudobulbs might reduce 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 $m^3 \cdot m^{-3}$ threshold could be acclimated to have similar values to that of the 0.45 $m^3 \cdot m^{-3}$ threshold, 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.

WUE

As the irrigation amount decreased with the decreasing θ threshold, the WUE increased inversely to the irrigation amount (Table II-3). Although the total water volume applied at 0.25 $m^3 \cdot m^{-3}$ was only 48% of that used by the plants grown at 0.55 $m^3 \cdot m^{-3}$, 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 $m^3 \cdot m^{-3}$ treatments had significantly higher WUE with similar biomasses and reduced water use compared to the 0.55 $m^3 \cdot m^{-3}$ treatment. In general, WUE is enhanced by deficit irrigation in various crops (Du et al., 2010; Rafi et al., 2019). Burnett and van Iersel (2008) also reported that *Gaura lindheimeri* survived at a θ ranging from 0.10 to 0.45 $m^3 \cdot m^{-3}$, and the WUE of the plants increased with decreasing θ thresholds.

Table II-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 ($m^3 \cdot m^{-3}$).

θ threshold ($m^3 \cdot m^{-3}$)	Irrigation amount (mL)	WUE ($g \cdot mL^{-1}$)
0.55	2,707 a[z]	2.7 c
0.45	2,060 b	3.5 b
0.35	1,727 c	3.9 b
0.25	1,307 d	5.0 a

[z] Means separation among the θ threshold treatments followed analysis of variance (ANOVA) with Duncan's multiple range test at $\alpha = 0.05$.

Nevertheless, these researchers recommended a θ of 0.25 $m^3 \cdot m^{-3}$ as the optimum θ threshold following consideration of water use and marketable plant quality. Similarly, marketable *Hibiscus acetosella* can be achieved when the plants are grown at a moderate θ threshold of 0.35 $m^3 \cdot m^{-3}$, even though the plants also withstand their growth at 0.10 $m^3 \cdot m^{-3}$ (Bayer et al., 2013). Therefore, to recommend an optimal θ threshold setpoint, water usage, and the quality of crop growth should be considered. In the case of *Cymbidium*, they were maintaining a θ threshold ranging from 0.35 to 0.45 $m^3 \cdot m^{-3}$ produced quality *Cymbidium* with comparatively little water.

Conclusion

Our study showed that the precision 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 of managing irrigation precisely. However, although coir dust was used as a fine substrate in the present 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 $m^3 \cdot m^{-3}$ provided adequate θ values for plant growth and photosynthesis, and the 0.35 and 0.45 $m^3 \cdot m^{-3}$ 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 $m^3 \cdot m^{-3}$ produced quality young *Cymbidium*. Consequently, if a precision irrigation system using a soil moisture sensor is used, it will be able to save water use and produce quality *Cymbidium*.

Like the efficient θ threshold treatments included in the EAW range, the matric potential ranges from –5 to –2.6 kPa could be considered when a grower decides the irrigation setpoint 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 a quality *Cymbidium* production strategy with more efficient water use.

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CHAPTER III

Efficient Fertilization Rate for Young *Cymbidium* Grown in Coir Dust Substrate Using a Precision Irrigation System

ABSTRACT

This study was conducted to investigate the optimal fertilization rate for producing *Cymbidium* using a precision automated irrigation system for efficient water and nutrient use during 52 weeks. One-year-old *Cymbidium* 'Hoshino Shizuku' plants were grown in coir dust as a substrate with a θ of 0.35 $m^3 \cdot m^{-3}$. The numbers of leaves and pseudobulbs, chlorophyll content of the plants were linearly increased with increasing fertilization rate at harvest. The plants grown under ×0.5 fertilization rate had a significantly smaller leaf, lead-bulbs, and shoot biomass than the other fertilization rates. Leaf length and width increased quadratically as the fertilization rate increased; there was a little reduction in leaf length as the fertilization rate increased from ×1.5 to ×2.0. Lead-bulbs were also influenced by fertilization rates quadratically; the fertilization rate from ×1.0 improved the lead-bulbs size compared with the other fertilization rates. Net CO_2 assimilation rate and shoot biomass also displayed a similar trend to leaf size. Therefore, ×1.0 fertilization rate was the most efficient fertilization rate to grow young *Cymbidium* when the plants were grown in coir dust substrate using a precision irrigation system.

INTRODUCTION

Irrigation management is closely related to nutrient use efficiency (Warren and Bilderback, 2005). Recently, the development of precision irrigation systems with various sensor technology provided more efficient water use for ornamental crop production, improved sustainability, and reduced production costs (Jahromi et al., 2018). These systems allowed efficient irrigation for crops through providing needed water precisely, thus improving water and nutrient use efficiency and preventing leaching by reducing runoff (Warsaw et al., 2009). In potted plant production, controlled-release fertilizer (CRF) is widely used since it can provide plants with appropriate nutrition and minimize runoff by releasing nutrients gradually (Cox, 1993; Broschat and Moore, 2007), which is more efficient in nutrient management with less leaching than water-soluble fertilizers (Chen et al., 2001a). Therefore, several studies investigated CRFs to improve water and nutrient efficiency in many potted plants such as petunia, basil, dill, parsley, sage, conifers, and lavender by using the soil moisture sensor-based precision irrigation system (Alem et al., 2015; Pershey et al., 2015; Zhen and Burnett, 2015; Currey et al., 2019).

Cymbidium hybrids have been considered the top commercial orchid in the World during the past decades because the cut flower and potted *Cymbidium* fetch the highest price (Lopez and Runkle, 2005; De et al., 2014). Although commercial *Cymbidium* plants are classified as terrestrial plants which usually prefer keeping the potting media moistened compared with epiphyte at all time (Lee, 2018), coarse particle substrates such as bark are commonly used to avoid too wet substrate conditions in conventional *Cymbidium* production because the plants are easily damaged on their roots by high substrate moisture levels (De et al., 2014). In the preceding study, a soil moisture sensor-based automated irrigation system could successfully grow *Cymbidium* with a fine particle substrate (coir dust) without any root diseases or leaching (Chapter I). Also, substrate volumetric water content (θ) from 0.35 to 0.45 $m^3 \cdot m^{-3}$ showed suitable water use efficiency and plant growth (Chapter II). However, the reduced irrigation may require adjustment of fertilization rates for the efficient *Cymbidium* production as the leachate amount was reduced. An investigation of the appropriate fertilization rate is needed in a precision irrigation system and the optimal substrate moisture levels.

CRFs are usually applied in *Cymbidium* production because it can supply constant low levels of nutrients that might provide nutrition stability, help minimize leaching, reduce plant damage, and improve the overall fertilizer use efficiency (Park et al., 2018). CRF has been commonly used in conventional *Cymbidium* production combined with the low water, and nutrient holding capacity of traditional container substrates bark, resulting in about 75% of the water with dissolved fertilizer is lost by leaching (Lee et al., 2014). However, growers need to consider greater regard toward nutrient use efficiency and retention for their profitable crop production due to increasing fertilizer costs (Altland and Locke, 2013). Although precision irrigation can increase water and nutrient use efficiency by reducing leachate, few studies had quantified both water and nutrient use efficiency when precision irrigation system was applied with CRFs.

Therefore, this study was conducted to investigate the effect of various fertilization rates of CRF on the growth and flowering of *Cymbidium* using the precision automated irrigation system. For each growth stage, CRF rates were determined to consider as common fertilizer usage in conventional *Cymbidium* production (Personal communication with experienced cymbidium grower). The objectives of the present study were 1) to compare the growth of young *Cymbidium* at various fertilization rates while maintaining θ at 0.35 $m^3 \cdot m^{-3}$ continuously using a soil moisture sensor-based irrigation system, and 2) to find the optimum CRF rates for quality production of *Cymbidium* with enhanced WUE and nutrient use efficiency.

MATERIALS AND METHODS

Plant, Substrate Materials and Growth Conditions

One-year-old *Cymbidium* ‘Hoshino Shizuku’ plants (Bio-U. Ltd., Zentuji, Kagawa, Japan) were obtained from a commercial orchid nursery (Haepyeong Orchids Farm, Gongju, Korea) on March 29, 2019. The plants were manually watered for 5 weeks to acclimate them to the experimental greenhouse environment, located in Seoul National University Farm, Suwon, Korea. After washing all the roots, the plants were transplanted into 1,330 mL plastic pots (15 × 13 cm, diameter × 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 to each substrate for root stabilizing to the new substrates. Plants were fully irrigated on July 6, 2019 and were not irrigated until the automated irrigation began on June 14, 2019. When the treatments began on July 6, the number of leaves, length and width of the uppermost fully expanded leaf, the number of pseudobulbs, the widest pseudobulb diameter, and chlorophyll content were 15.3 ± 0.42 (mean ± SE, n = 12), 39.9 ± 0.58 cm, 1.9 ± 0.01 cm, 1 ± 0.00, 19.4 ± 0.23 mm, and 52.8 ± 1.37, respectively. The experiment was carried out for 52 weeks, from July 6, 2019 to July 1, 2020. The temperature, vapor pressure deficit, and daily light integral (DLI) 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) (Fig. III-1).

Moisture Retention and Chemical Properties of Substrate

Moisture retention curve of coir dust was investigated to determine the proper irrigation threshold volumetric water content (VWC, θ) level using a Hyprop (Meter Group, Pullman, WA, USA). The pH and electrical conductivity (EC) of the substrate were determined by the substrate: distilled water (1:5, v/v) method using a pH and EC meter (Orion 3 Star; Thermo Fisher Scientific Inc., Beverly, MA, USA). The EC of the substrates after harvest was determined again.

Precision Automated Irrigation System and Fertilization Rates

Six FDR soil moisture sensors (EC-5; Meter Group) were connected to a data logger (CR1000; Campbell Scientific) to measure and control the VWC (θ) in pots. A data logger powered the soil moisture sensors with 2.5 V excitation, and substrate-specific calibration was conducted according to the equation; $\theta = 0.1667 \times$ sensor output (mV) –54.446 ($r^2 = 0.89$). Each sensor (5.5 cm length and 1.0 cm width) was inserted diagonally experimental unit dropped below the assigned θ threshold, the data logger opened the solenoid valve to the experimental unit for 20 s. Plants were irrigated using a spray stake (PC Spray Stakes; Netafim, Tel Aviv, Israel) with pressure-compensated drip emitter (PCJ HF-20L, Netafim), and each irrigation event

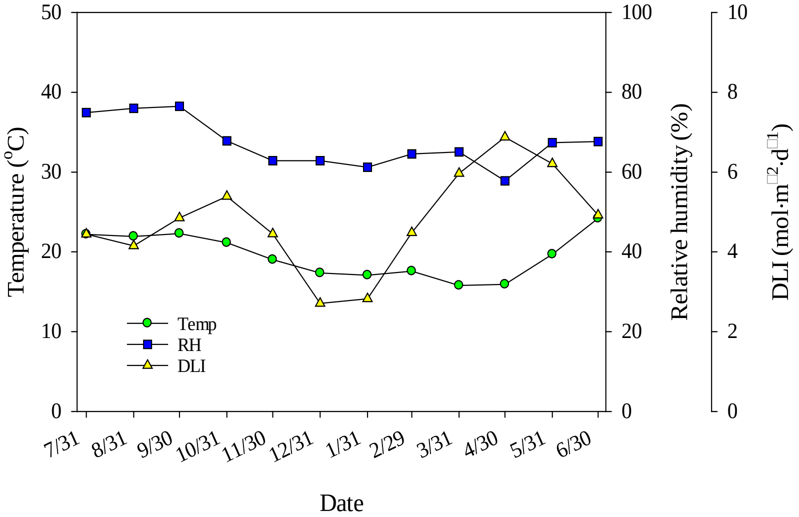

Fig. III-1. Monthly average air temperature (ºC), relative humidity (RH, %), and daily light integral (DLI, mol·m^{-2}·d^{-1}) during the experiment.

provided ca. 20 mL for plants. A data logger recorded each irrigation application, and the daily and total amount of water applied to the plants were subsequently calculated.

In conventional *Cymbidium* production, ca. 4 g per plant of CRF have been typically used for their vegetative growth in the 1-year-old plants (*Personal communication with the experienced cymbidium grower*). Hence, these fertilization rates were regarded as standard fertilization rates in the present study, and the four different rates (×0.5, ×1.0, ×1.5, or ×2.0) of standard rates were applied; CRF (Osmocote Plus, 15N-4.8P-10.8K + 2Mg + trace elements; Everris International B.V., Heerlen, The Netherlands) was applied at 2, 4, 6, or 8 g per plant.

Plant Growth and Flowering Characteristics

At the end of the experiment, the total number of leaves, the length and width of the uppermost fully expanded leaf, the number of pseudobulbs, root length, and the fresh and dry weight of shoots and roots were measured. The pseudobulb diameter was measured at the widest point of the pseudobulb in mother bulbs, lead bulbs, and flowering bulbs 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 samples in an oven at 80°C for 7 d.

Photosynthetic Gas Exchange

Photosynthetic gas exchange was measured using a portable photosynthesis measuring system (Li 6400; Li-Cor Co., Inc., Lincoln, NE, USA) from 11:00 to 14:00 after 50 weeks of growth for one week. 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 photosynthetic photon flux density at 1000 $\mu mol \cdot m^{-2} \cdot s^{-1}$. 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 of gas exchange had been achieved, the net CO_2 assimilation rate was determined.

Experimental Design and Statistical Analysis

The experiment used a randomized complete block design with four treatments and three blocks. The effects of fertilization rate and growth stage on growth parameters were analyzed by three-way analysis of variance using SAS 9.4 (proc GLM; SAS Institute, Cary, NC). When ANOVA indicated significance, means were separated using pairwise comparisons at α = 0.05. The growth parameters, photosynthesis, and EC of substrate were analyzed using linear and quadratic regression analysis. Curve fitting was done using SigmaPlot (SigmaPlot 14.0; Systat, Systat Software Inc., San Jose, CA, USA).

RESULTS AND DISCUSSION

Performance of the Precision Irrigation System

The soil moisture sensor-based automated irrigation system properly maintained the θ of the treatments as planned for 52 weeks (Fig. III-2). The θ threshold treatment (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 0.35 $m^3 \cdot m^{-3}$. The θ in each pot was consistently maintained just above the allocated threshold throughout the experiment, and the θ values during the 52 weeks were 0.38 ± 1.2 (mean ± SD).

Vegetative Growth of *Cymbidium*

The number of leaves and pseudobulbs of 1-year-old *Cymbidium* plants were linearly increased as the fertilization rate increased from ×0.5 to ×2.0 (Fig. III-3A-B). These results were consistent with several previous observations that a high nutrient application produced more leaves in *Cymbidium* hybrids than low nutrient levels (De et al., 2014, Pun, 2019). However, leaf length and width increased as the fertilization rate increased, but they showed a quadratic relationship; there was a less increase in leaf length as the fertilization rate further increased from ×1.5 to ×2.0 (Fig. III-3C and D), indicating ×0.5 fertilization rate was not sufficient to produce broad leaves of 1-year-old *Cymbidium*. Naik et al. (2010) reported that the leaf

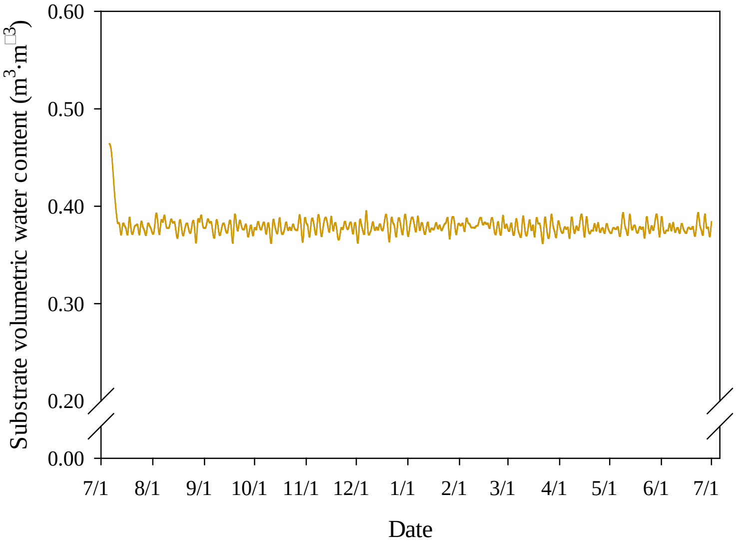

Fig. III-2. Substrate volumetric water content (θ, $m^3 \cdot m^{-3}$) changes during the experiment (July 6, 2019-July 1, 2020) using a soil moisture sensor-based automated irrigation system. Set θ threshold was designated at 0.35 $m^3 \cdot m^{-3}$ for 1-year-old *Cymbidium* ‘Hoshino Shizuku’.

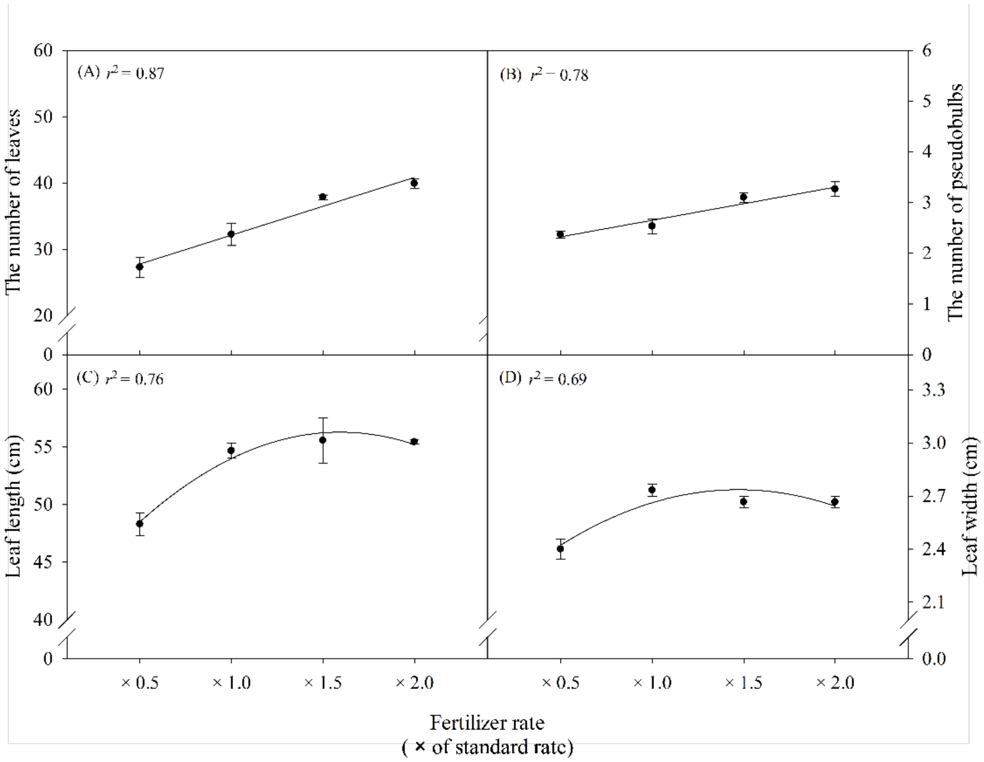

Fig. III-3. The influence of fertilization rate (× of standard rates) and growth stage on the number of leaves (A) and pseudobulbs (B), and leaf length (C) and width (D) produced on 1-year-old *Cymbidium* ‘Hoshino Shizuku’ after 52 weeks of growth (n = 12). The standard fertilization rate for the plants was 4 g per plant.

width of *Cymbidium* 'Pine Clash Moon Venus' did not show a significant difference among eight NPK treatment levels for two years, but the plants grown under control treatment (without additional fertilizer) had significantly smaller leaf width than other fertilizer treatments. Overall, the shoot growth of the plants was promoted as the fertilization rate increased (Fig. III-4).

Pseudobulb is a major organ that stores carbohydrates through photosynthesis in orchids, including *Cymbidium*, *Cattleya*, *Oncidium*, and *Paphiopedilum* (De et al., 2015). When a pseudobulb of orchid is sufficiently matured, the plants stop their leaf growth on the pseudobulb, and then the plants can emerge and form a new shoot from the axillary bud on the pseudobulb (Hew and Yong, 2004). During vegetative growth for over three years, this situation commonly happens sequentially in *Cymbidium*. There were no differences observed in mother-bulb regardless of fertilization rates (Fig. III-5A). When leaves or pseudobulbs of orchids are fully expanded or matured, the plants usually export their stored assimilates to the growing shoot tip, young expanding leaves, and new pseudobulbs as sinks (Yong and Hew, 1995; Hew and Yong, 2004). These results implicated that the mother-bulb might act as a source to nourish other sink organs such as newly emerged leave and pseudobulbs. In the present study, the mother-bulb size was larger than the other pseudobulbs, implicating that the mother-bulb was sufficiently matured to help other pseudobulbs. Lead-bulbs of the plants were influenced by fertilization rates quadratically; the fertilization rate from ×1.0 improved the lead-bulbs size compared with the other fertilization rates (Fig. III-5B-C).

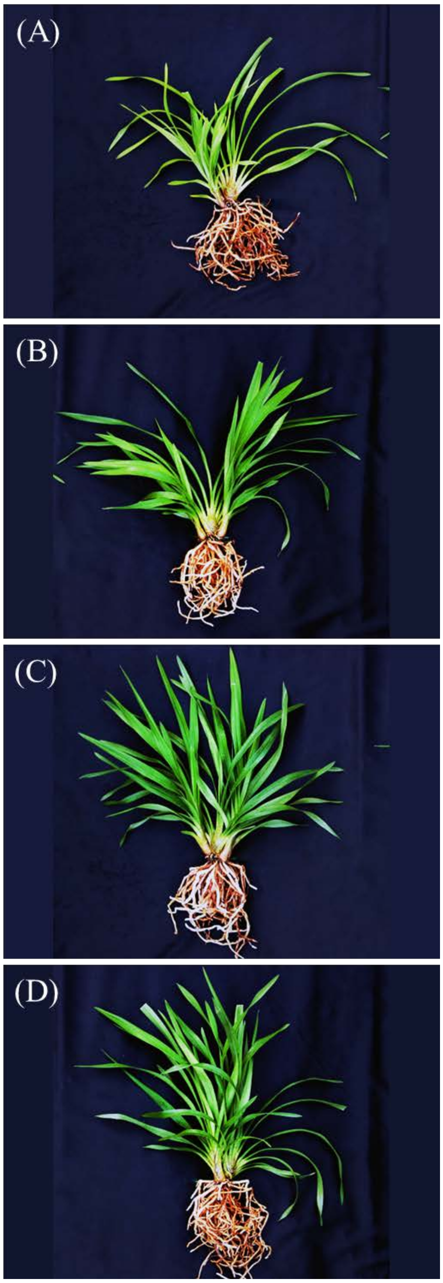

Fig. III-4. Growth of 1-year-old *Cymbidium* ‘Hoshino Shizuku’ grown under ×0.5 (A), ×1.0 (B), ×1.5 (C), and ×2.0 (D) of standard rates using a precision irrigation system for 52 weeks. The standard fertilization rate for the plants was 4 g per plant.

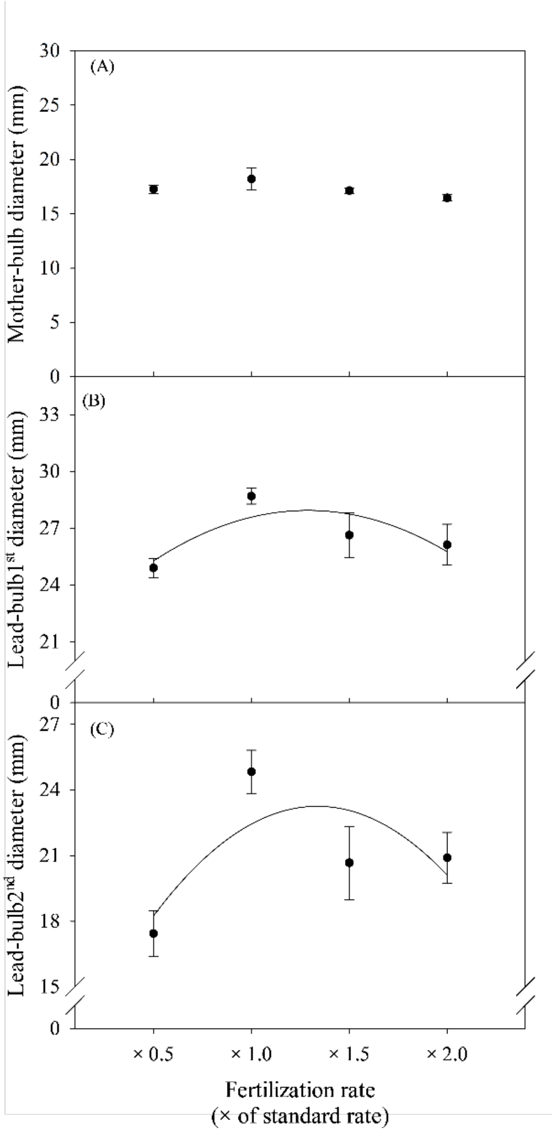

Fig. III-5. The influence of fertilization rate (× of standard rates) on the growth of mother-bulb (primary pseudobulb originated from mericlone), lead-bulb1st (firstly emerged pseudobulb), and lead-bulb2nd (secondary emerged pseudobulb) produced on 1-year-old Cymbidium 'Hoshino Shizuku' after 52 weeks of treatment (n = 12). The standard fertilization rate for the plants was 4 g per plant.

Chlorophyll Content and Photosynthetic Assimilation Rate

Similar to the number of leaves and pseudobulbs, chlorophyll content of the *Cymbidium* also linearly increased with increasing fertilization rate from ×0.5 to ×2.0 (Fig. III-6A). The chlorophyll content is closely related to nitrogen content. Supplying nitrogen promotes photosynthetic rate and capacity (Mohotti, 2002; Netto et al., 2005). Insufficient fertilizer supply leads to a decrease in chlorophyll content, which lowers the photosynthesis rate, and producing quality *Cymbidium* requires proper fertilization management considering the environment and plant conditions (Kim et al., 2015). The plants grown under ×0.5 fertilization rate showed a significantly low photosynthetic rate, while there was no significant difference among the other fertilization rates (Fig. III-6B). The pseudobulb serves as a buffer against nutrient deficiency and drought stress because of its ability to retain nutrients and water (Yong and Hew, 1995; Ng and Hew, 2000). Those features may maintain normal physiological functioning for more extended periods under nutrient and water deficits (Zhang et al., 2018). However, the plants grown under ×0.5 fertilization rate showed reduced photosynthesis and limited shoot growth. These results implicated that ×0.5 fertilization rate was a nutrient deficiency or insufficient conditions for the growth of young *Cymbidium*. Although fresh and dry root weight of the plants was not affected by fertilization rate, fresh and dry shoot weight also showed a similar tendency to photosynthesis (Fig. III-7). The EC values of coir dust were significantly different among the fertilization rates at harvest (Fig. III-8).

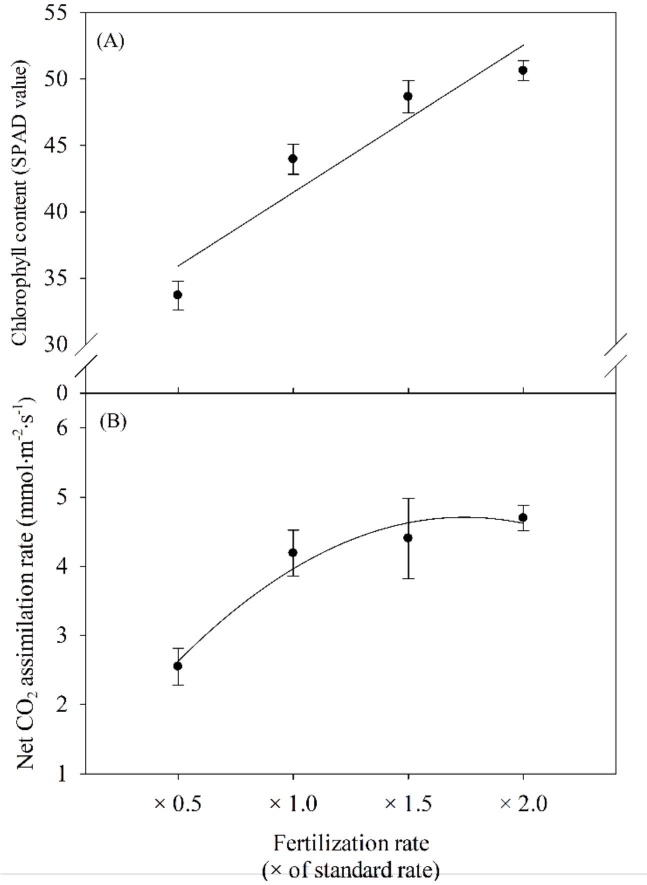

Fig. III-6. The influence of fertilization rate (× of standard rates) and growth stage on chlorophyll content (n =12) and net CO_2 assimilation rate (n = 9) of 1-year-old *Cymbidium* 'Hoshino Shizuku' at 50 weeks of treatment. The standard fertilization rate for *Cymbidium* was 4 g per plant.

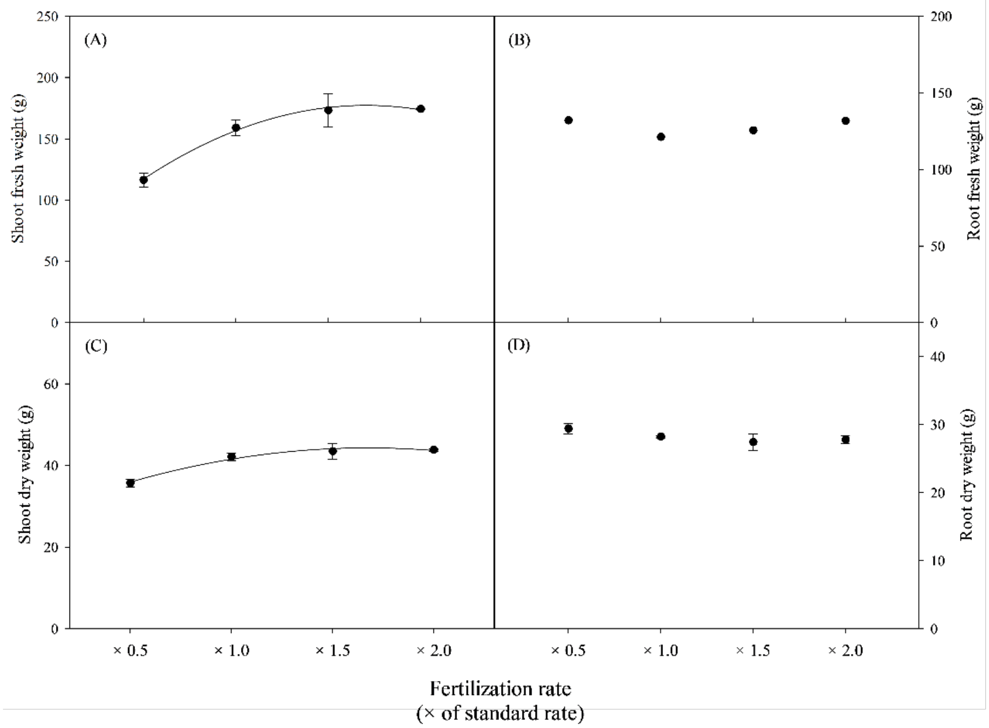

Fig. III-7. The influence of fertilization rate (× of standard rates) and growth stage on fresh and dry weights of 1-year-old *Cymbidium* 'Hoshino Shizuku' at the harvest after 52 weeks of growth under experimental conditions (n = 12). The standard fertilization rate for *Cymbidium* was 4 g per plant.

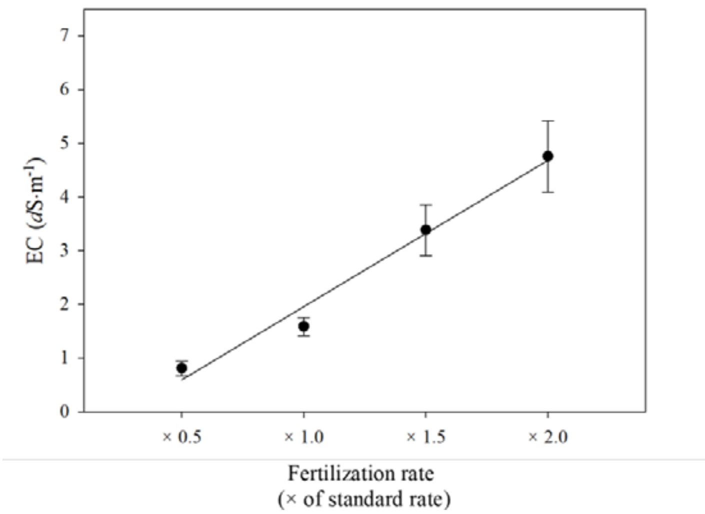

Fig. III-8. Relationship between fertilization rate and electrical conductivity (EC) of coir dust after growing 1-year-old *Cymbidium* ‘Hoshino Shizuku’ for 52 weeks (n = 9). The standard fertilization rate was 4 g per plant.

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CONCLUSIONS

This study showed that the FDR soil moisture sensor-based automated precision irrigation system successfully produced *Cymbidium* regardless of the substrate. The coarse substrates required about 8 times more water than the fine substrates to maintain a similar matric potential, but the plant growth was similar among the substrates, except for the plants grown in a commercial growing mix. These results were not consistent with previous observations that lowering growth of *Cymbidium* in bark; this might be because the substrate moisture conditions were different from the tested substrates. Nevertheless, bark was not a suitable substrate for *Cymbidium* since it was water and nutrient inefficient compared with the fine substrates. Fine substrates provided many benefits for water- and nutrient-holding capacities, increasing water and nutrient efficiency. As orchid species require enough aeration due to their specialized root system, growers have been reluctant to use fine substrates because of irrigation management difficulty. However, the present results showed that the soil moisture sensor-based automated irrigation system could successfully produce *Cymbidium* with fine substrates with much more efficient irrigation than the conventional way.

Coir dust was used as a fine substrate in the present 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 $m^3 \cdot m^{-3}$ provided adequate θ values for plant growth and photosynthesis, and both

0.35 and 0.45 $m^3 \cdot m^{-3}$ 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 $m^3 \cdot m^{-3}$ produced quality young *Cymbidium*. Like the efficient θ threshold treatments included in the EAW range, the matric potential ranges from –5 to –2.6 kPa could be considered adequate when a grower decides the irrigation setpoint for producing *Cymbidium* using a precision automated irrigation system with a fine substrate.

Fertilization and irrigation methods depend on the substrate physicochemical properties such as moisture retention capacity and nutrient holding capacity. Finding optimal fertilization rate is necessary to use a precision irrigation system for improving WUE and nutrient use efficiency. While the number of leaves and pseudobulbs of *Cymbidium* tended to increase as the amount of fertilizer increased, the standard fertilization rate could satisfy overall vegetative growth and biomass. Therefore, ×1.0 fertilization rate was the most efficient rate to grow young *Cymbidium* when the plants grown in coir dust substrate using a precision irrigation system. However, a further detailed study examining the long-term effects of fertilization rate on growth and flowering would be needed. Finding the optimum fertilization rate depending on their growth stage and seasonal effects would provide a quality *Cymbidium* production strategy with more efficient nutrient use for an extended period of cultivation. These results could help develop new irrigation and fertilization strategies with improving water and nutrient use efficiency for commercial *Cymbidium* growers.

ABSTRACT IN KOREAN

심비디움을 포함한 대다수의 난과 식물은 벨라민층으로 덮인 독특한 뿌리 구조를 갖고 있기 때문에 과습에 매우 취약하며, 만약 과습에 노출될 경우, 박테리아 감염에 의한 뿌리썩음병이 발생하기 쉽다. 따라서 국내뿐만 아니라 해외의 대다수 농가에서는 과습을 방지하기 위해 바크와 같은 입자가 굵은 상토를 배지로 사용하며, 이로 인해 매 관수 시 마다 관수량의 약 75%가 용탈로 버려진다. 따라서 본 연구에서는 굵은 입자 상토를 사용하는 관행 관수 방식을 개선하기 위해 상토의 수분을 정밀하게 조절할 수 있는 FDR 토양 수분 센서 기반의 정밀 자동 관수 시스템과 코이어 등 다양한 상토를 사용하여, 심비디움 재배에 FDR 토양 수분 센서의 적용 가능성과 적용 시 관수 효율, 적정 상토 수분 함량 및 적정 시비량을 확인하였다. 제1장에서는 관행 재배 상토인 바크를 비롯하여 코코넛 허스크칩, 코이어, 그리고 원예용 상토를 포함한 4종의 상토에 FDR 토양 수분 센서 기반의 정밀 자동 관수 시스템을 이용해 심비디움 재배 시 상토 수분 조절에 FDR 토양 수분 센서를 적용할 수 있는지 확인하였다. 제2장에서는 제1장의 결과를 바탕으로, 코이어 상토와 FDR 토양 수분 센서 기반의 정밀 관수

시스템을 이용하여 심비디움 재배 시 적정 상토 수분 함량을 확인하였으며, 마지막 제3장에서는 앞선 연구를 통해 확인된 상토 수분 함량을 기반으로 유식물 심비디움의 생육에 필요한 적정 비료 시비율을 확인하였다. 본 연구를 통해서 FDR 토양 수분 센서를 심비디움 재배에 적용할 수 있다는 것을 확인하였고, 상토의 물리적 특성을 고려해 matric potential 값을 기준으로 관수 시점을 설정하였을 때, 상토의 종류는 심비디움의 생육에 유의미한 영향을 미치지 못하였다. 하지만 대립인 바크나 코코넛 허스크칩과 달리 소립인 코이어나 원예용 상토를 사용했을 경우, 대립 상토를 사용해 심비디움을 재배했을 때 보다 약 8배의 물 사용량을 줄일 수 있었다. 이 결과를 바탕으로 소립인 코이어와 FDR 토양 수분 센서 기반 정밀 관수 시스템을 이용하여 4수준의 상토 수분 함량에 심비디움을 재배했을 때 관수 시점이 0.25 $m^3 \cdot m^{-3}$에서 수분 이용 효율은 가장 높았지만, 생육과 광합성 모두에서 다른 처리에 비해 낮았으며 생육 또한 가장 저조하였다. 반면, 0.35~0.45 $m^3 \cdot m^{-3}$ 처리는 0.25 $m^3 \cdot m^{-3}$ 처리에 비해 수분 이용 효율은 낮았지만 수분 이용 효율과 영양생장, 그리고 광합성을 고려했을 때, 물을 가장 효율적으로 사용하며 생장도 만족시킬 수 있는 상토 수분 함량임을 확인할 수 있었다. 유식물 심비디움의 재배에 있어 앞선 연구를 통해 확인된

결과 값을 기준으로 동일한 정밀 관수 시스템을 이용하여 심비디움 생장에 적합한 시비율을 확인하였으며, 비교를 위해 관행 재배에서 사용하는 완효성 비료 시비량을 기준으로 0.5, 1.0, 1.5, 2.0배의 완효성 비료를 시비하고 약 1년 동안 생육을 확인하였다. 그 결과 1.0배 이상의 완효성 비료를 시비하였을 때 0.5배 시비량 보다 향상된 생육을 보였지만, 1.0배 이상의 시비량 사이에서는 시비량 차이에 따른 유의미한 차이는 나타나지 않았다. 위의 결과를 종합해보면 유식물 심비디움의 생육을 위해 코이어 상토와 정밀 관수 시스템을 사용할 경우, 관행 시비량과 같은 양의 시비를 하는 것이 가장 효과적일 것으로 판단되었다. 다만, 본 실험에서는 유식물 심비디움만을 대상으로 생육에 적합한 시비량을 확인하였기 때문에 심비디움의 육묘부터 개화까지 모든 작형에 알맞은 관수 전략을 마련하기 위해서는 보다 정밀한 양분 실험이 필요할 것으로 판단된다.