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Growth Characteristics in Response to Soil Moisture Content with Sensor-based Automated Irrigation System in *Chrysanthemum naktongense* Nakai

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***Abstract. Chrysanthemum naktongense* Nakai is a wild plant with ornamental and medicinal properties. As the demand for wild plant products increases, stable production methods are necessary to support industrial use. However, wild plants are typically grown under open-field conditions, and information on their irrigation practices in greenhouse cultivation is limited. In this study, we investigated the effects of soil moisture content in greenhouse cultivation on the growth and irrigation water use efficiency of *C. naktongense* Nakai seedlings. Using a sensor-based automated irrigation system, the soil moisture content was maintained at four volumetric water content levels: 0.3, 0.4, 0.5, and 0.6 $m^3 \cdot m^{-3}$. The leaf area and fresh and dry weights of the leaves and stems decreased significantly at 0.3 $m^3 \cdot m^{-3}$, whereas the highest values were observed at 0.5 $m^3 \cdot m^{-3}$, with photosynthetic ability showing a similar trend. Irrigation water use efficiency was calculated based on the total dry weight and cumulative irrigation amount during the experiment, was highest in the 0.5 $m^3 \cdot m^{-3}$ treatment. These findings contribute to the determination of the water requirements of *C. naktongense* Nakai and to develop an efficient irrigation practice for the domestication of this crop in a greenhouse.**

Wild plants have the potential for ornamental and medicinal uses, and their collection and use are essential for horticultural activities. These plants are native to their habitats; therefore, they have adapted to each region over a long period of time. Their high environmental adaptability makes them easy to cultivate and use wild plants as commercial crops (Shelef et al. 2017). Considering that the global market for natural plant products has increased dramatically (Aschemann-Witzel et al. 2021), it is necessary to provide a stable supply for the industrialization of wild plants.

The genus *Chrysanthemum* comprises a well-known group of ornamental and medicinal flowers that are cultivated worldwide. The pharmacological functions of this genus have been well established (Chen et al. 2021; Hodaei et al. 2021; Liu et al. 2010). *C. zawadskii* var. *latilobum* is an herbaceous perennial plant distributed in East Asia, including Korea, China, and Japan. The leaves and stems of this plant, which contain various phytochemicals, such as flavonoids, glycosides, and polyphenols, are harvested for medicinal uses or used as extracts, such as tea and raw materials for medicine and cosmetics (Kim et al. 2012; Rahman and Moon 2007; Seo et al. 2010; Shim et al. 2012).

Greenhouse cultivation makes crop production more efficient through environmental control and protected management. This results in increased productivity and enables the production of products that cater to year-round demand. Wild plants are normally cultivated under open-field conditions. Therefore, introducing these plants into greenhouse cultivation can facilitate stable use of natural plant products. Additionally, greenhouse-cultivated plants can serve as alternatives to wild plants for medicinal purposes (López-Laredo et al. 2012).

Appropriate irrigation practices are important for greenhouse cultivation. Among the underground factors, the soil moisture level is one of the primary factors for plant growth and development (Boyer 1982). Moisture levels determine various plant physiological processes such as photosynthesis, transpiration, and the consequent growth rate (Li et al. 2019; Sharp 1996; Zlatev and Lidon 2012). Therefore, irrigation scheduling with monitoring of soil moisture is essential for greenhouse crops to support the estimation of crop growth (Nikolaou et al. 2019). With the development of soil moisture sensors, sensor-based irrigation can be used for efficient irrigation management. This irrigation system has been used in horticultural plant cultivation to enhance water use efficiency and crop yield by providing the optimal amount of moisture for plant water requirements (An et al. 2021; Bacci et al. 2008; Nam et al. 2020).

Previous studies on *C. zawadskii* var. *latilobum* have primarily focused on practical cultivation techniques, such as cutting, application of plant growth regulators, and selection of appropriate substrates for the cultivation of ornamental plants (Jin et al. 1998; Shin and Yun 2006; Yoo et al. 1999). Additionally, some studies have reported the medicinal activities and extraction conditions of phytochemicals from plants (Chung and Jeon 2011; Kim et al. 2016; Li et al. 2014). We considered cultivation using pots with substrates to develop a technique for the stable year-round production of this wild plant in a greenhouse. However, to the best of our knowledge, there is a lack of information on irrigation practices for this plant using substrates in greenhouses. To develop an irrigation system for a greenhouse, it is necessary to determine the growth characteristics based on substrate moisture levels. This study was conducted to observe the growth characteristics and irrigation water use efficiency at different substrate moisture levels with a sensor-based automated irrigation system in *C. zawadskii* var. *latilobum*.

Materials and Methods

Plant materials and growth conditions. Two-month-old *C. zawadskii* var. *latilobum* seedlings were transplanted into 12-cm plastic pots (~600-mL volume) filled with a soilless substrate (Sunshine Mix #4; Sun Gro Horticulture, Agawam, MA, USA). Plants were fertilized with controlled-release fertilizer (PurKote 14–14–14 90D; Pursell Agri-Tech, Sylacauga, AL, USA) at a rate of 4 g per pot. Before the start of treatments, all plants were cultivated in a greenhouse for 4 weeks for acclimatization. The average temperature and daily light integral during the acclimatization period were 31.6 °C and 2.42 $mol \cdot m^{-2} \cdot s^{-1}$, respectively. The plants

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were irrigated once a week using overhead irrigation. At the start of treatment, the number of leaves, plant height, and soil and plant analyzer development (SPAD) values were 18.5, 13.0, and 43.8 cm, respectively.

After the acclimatization period, the experiment was conducted for 12 weeks. The light intensity, temperature, relative humidity, and CO_2 concentration were monitored using a QSO-S quantum sensor (Apogee Instruments, Logan, UT, USA) and an auto control system SH-MV260 (SOHA Tech, Seoul, Korea) sensors connected to a CR1000X data logger (Campbell Scientific, Logan, UT, USA).

Sensor-based irrigation treatment with different volumetric water contents. A sensor-based automated irrigation system with frequency-domain reflectometry soil moisture sensors was used in this study for precise control of volumetric water content (VWC) in pots. EC-5 soil moisture sensors (Meter Group, Pullman, WA, USA) were connected to a data logger using an AM 16/32B multiplexer (Campbell Scientific). The irrigation rate was controlled using drip stakes with emitters (Netafim, Tel Aviv, Israel), solenoid valves, and relay drivers (SDM-16AC/DC; Campbell Scientific). Before the VWC control, the soil moisture sensors were calibrated to the substrate used in this study. The equation for converting the sensor output value to the VWC value was [VWC (v/v, $m^3 \cdot m^{-3}$) = 0.1771 × sensor output (mV) − 52.968]. To prevent physical injury to the roots, the sensor was inserted ~2 cm from the middle of the pots. When the VWC readings of the sensors dropped below the assigned threshold, the pots were irrigated by opening the solenoid valves for 10 s at ~10 mL. Irrigation time and amount of water applied to the pots were monitored throughout the experiment.

The plants were treated with four VWCs: 0.3, 0.4, 0.5, and 0.6 $m^3 \cdot m^{-3}$. Each treatment consisted of three replicates, with each containing six replicates. The plants were placed in a randomized complete block design. Among the subreplicate units, irrigation time and VWC measurements for each replication group were performed based on the VWC levels in a single pot. The VWC setpoints were based on the substrate matrix potential previously reported by Nam et al. (2020). The approximate substrate matric potentials were −10 kPa at 0.3 $m^3 \cdot m^{-3}$, −5 kPa at 0.4 $m^3 \cdot m^{-3}$, −3 kPa at 0.5 $m^3 \cdot m^{-3}$, and −2 kPa at 0.6 $m^3 \cdot m^{-3}$; therefore the setpoints used in this study were set to be represented in water buffering capacity (WBC) (0.3 $m^3 \cdot m^{-3}$), between WBC and easily available water (EAW) (0.4 $m^3 \cdot m^{-3}$), and in EAW (0.5 and 0.6 $m^3 \cdot m^{-3}$) (De Boodt and Verdonck 1972). Actual VWCs were maintained at similar set points throughout the experiment (Fig. 1).

Data collection and statistical analysis. The number of leaves, leaf area, SPAD value, and fresh and dry weights of the leaves, stems, and roots were measured at the end of the treatments. Irrigation water use efficiency (IWUE) was calculated as follows: [(dry weight at the end of treatments – dry weight at the start of treatments)/amount of irrigated water during the experiment].

To evaluate photosynthetic capacity at different VWC levels, light response curves were determined using a portable photosynthesis measuring system (LI-6800; LI-COR Co., Inc., Lincoln, NE, USA) at the end of the treatment. A fully expanded leaf was clamped onto a leaf chamber with a 1 × 3 cm aperture. Measurements were performed under light levels of 2000, 1500, 1000, 500, 200, 100, 50, and 0 $\mu mol \cdot m^{-2} \cdot s^{-1}$ photosynthetic photon flux density. The leaf temperature, relative humidity, CO_2 concentration, and airflow rate inside the chamber were set at 25 °C, 60%, 400 $\mu mol \cdot mol^{-1}$, and 600 $\mu mol \cdot s^{-1}$, respectively. Three plants from each treatment were used for the measurements.

Statistical analyzes were performed using analysis of variance with Statistical Analysis System (SAS) software (Windows version 9.4; SAS Institute Inc., Cary, NC, USA). Comparisons among treatment groups with different VWCs were carried out using

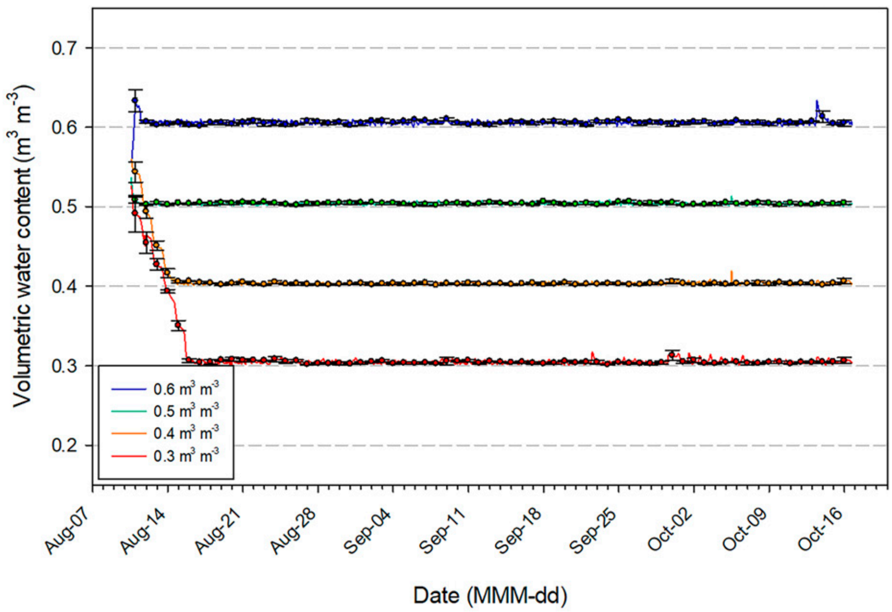

Fig. 1. Substrate volumetric water content levels (VWCs) in pots containing *Chrysanthemum naktongense* Nakai plants maintained using a sensor-based automated irrigation system (mean values ± *SD*). Plants were irrigated when the water content of the substrate decreased below each of the established set points of 0.3, 0.4, 0.5, and 0.6 $m^3 \cdot m^{-3}$ VWCs.

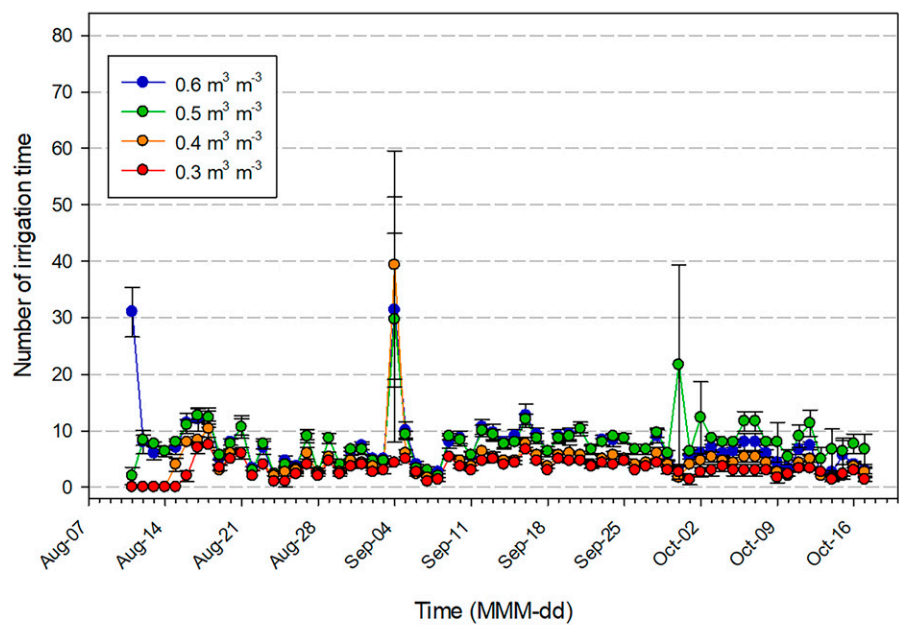

Fig. 2. The daily number of irrigation events (mean values ± *SD*) and cumulative number of average irrigation times in pots with *Chrysanthemum naktongense* Nakai plants maintained using a sensor-based automated irrigation system. Plants were irrigated when the water content of the substrate decreased below each of the established set points of 0.3, 0.4, 0.5, and 0.6 $m^3 \cdot m^{-3}$ volumetric water content levels.

Table 1. The growth characteristics of *Chrysanthemum naktongense* Nakai plants treated with different volumetric water content levels (0.3, 0.4, 0.5, and 0.6 $m^3 \cdot m^{-3}$) in the pots for 12 weeks.

Treatment ($m^3 \cdot m^{-3}$)	No. of leaves	Leaf area (cm^2)	SPAD value	Fresh wt (g) Leaf	Fresh wt (g) Stem	Fresh wt (g) Root	Dry wt (g) Leaf	Dry wt (g) Stem	Dry wt (g) Root	IWUE[i] ($kg \cdot m^{-3}$)
0.6	52.73	428.17 a[ii]	47.41	14.77 ab	2.04 ab	3.37	1.45 ab	0.47 a	0.44	0.22
0.5	55.78	472.98 a	49.45	16.57 a	2.78 a	4.19	1.54 a	0.50 a	0.53	0.25
0.4	45.07	319.26 b	48.77	11.19 bc	1.98 b	3.04	1.12 bc	0.40 ab	0.41	0.22
0.3	40.38	271.94 b	47.78	10.14 c	1.37 b	2.75	0.97 c	0.33 b	0.36	0.19
Significance (*P* values)	NS	**	NS	*	**	NS	*	*	NS	NS

[i] Indicates the irrigation water use efficiency (IWUE) per plant during the experiment.

[ii] Means (n = 3) within columns followed by different letters are significantly different according to Tukey's honestly significant difference test at $P < 0.05$.

NS, *, ** Nonsignificant or significant at $P < 0.05$ or 0.01, respectively.

SPAD = soil and plant analyzer development.

Tukey's honestly significant difference test to evaluate the growth characteristics with $P = 0.05$, as the threshold for statistical significance. Graph module analyzes were performed using the SigmaPlot software (version 10.0; SYSTAT Software, Inc., Chicago, IL, USA).

Results and Discussion

Sensor-based irrigation was used to maintain the set points for each treatment (Fig. 1). For ~10 weeks after the start of treatment, the number of irrigation events increased with increasing VWC setpoints (Fig. 2). However, the cumulative irrigation time in the 0.5 $m^3 \cdot m^{-3}$ treatment reversed the time in the 0.6 $m^3 \cdot m^{-3}$ treatment. At the end of treatment, the average cumulative time in each treatment group was 218.0, 314.7, 543.7, and 508.3 at 0.3, 0.4, 0.5, and 0.6 $m^3 \cdot m^{-3}$, respectively.

Although there were no statistically significant differences in the number of leaves, SPAD value, and root biomass in terms of fresh and dry weights, these growth parameters exhibited similar trends to the growth characteristics, leaf area, and leaf and stem biomass, which showed significant changes (Table 1 and Fig. 3). Specifically, the highest values of leaf area ($P < 0.01$) and fresh ($P < 0.05$ and 0.01, respectively) and dry weights ($P < 0.05$ and 0.05, respectively) of leaves and stems were observed in the 0.5 $m^3 \cdot m^{-3}$ treatment. However, in mean separation, there was no significant difference between 0.5 and 0.6 $m^3 \cdot m^{-3}$ treatments in the growth characteristics. Plants grown under the 0.3 $m^3 \cdot m^{-3}$ treatments exhibited the lowest values for all growth parameters. On the basis of the total dry weights and cumulative irrigation amounts, IWUE did not show significant differences among treatments, but it was the highest in 0.5 $m^3 \cdot m^{-3}$ treatment, followed by 0.4, 0.6, and 0.3 $m^3 \cdot m^{-3}$ treatments, showing a corresponding trend (Table 1).

Plants in open fields typically rely on precipitation or periodic irrigation, which creates fluctuations in soil moisture. However, sensor-based irrigation allows for the real-time management of soil moisture for crop growth, and this technology can have environmental and economic benefits by efficiently using water and fertilizer (Lichtenberg et al. 2013). In this study, sensor-based irrigation constantly controlled the substrate VWC setpoints in the pots (Fig. 1). Nam et al. (2020) reported that a constant substrate moisture level enhanced the growth and concentration of phenolic compounds in sweet basil compared with fluctuating conditions. Thus, sensor-based irrigation management is a suitable irrigation system for *C. zawadskii* var. *latilobum* cultivation because it conforms to the recent developments in information and communication technology–based horticulture.

The photosynthetic capacity in response to light intensity showed a trend similar to that of growth characteristics (Fig. 4). The highest assimilation rate at the light-saturation point was observed in the 0.5 $m^3 \cdot m^{-3}$ treatment, followed by the 0.6, 0.4, and 0.3 $m^3 \cdot m^{-3}$ treatments. In the 0.5 $m^3 \cdot m^{-3}$ treatment, as the light intensity increased, the assimilation rate increased in comparison with the assimilation rates in the other treatments.

Soil moisture levels change root water uptake and nutrient availability, consequently affecting plant growth rate (Passioura 2002). The physiological responses of soil moisture and plant growth to growth characteristics and productivity have been reported in several studies (Chaves et al. 2003; Li et al. 2019; Sharp 1996). In this study, biomass accumulation and increasing leaf numbers showed gradual saturating responses with increasing VWC levels, and low soil moisture significantly limited the growth of *C. zawadskii* var. *latilobum*. Leaf and stem biomass exhibited significant differences under varying soil moisture conditions, whereas root biomass showed no significant variation (Table 1). According to previous studies, root growth can be maintained to some extent unless water stress reaches an extreme drought level (Palta and Turner 2019). Additionally, as long as water availability remains above a critical threshold, root growth can continue

Fig. 3. The effects of various volumetric water content levels (0.6, 0.5, 0.4, and 0.3 $m^3 \cdot m^{-3}$) in the pots on the growth characteristics of *Chrysanthemum naktongense* Nakai plants after 12 weeks of cultivation periods.

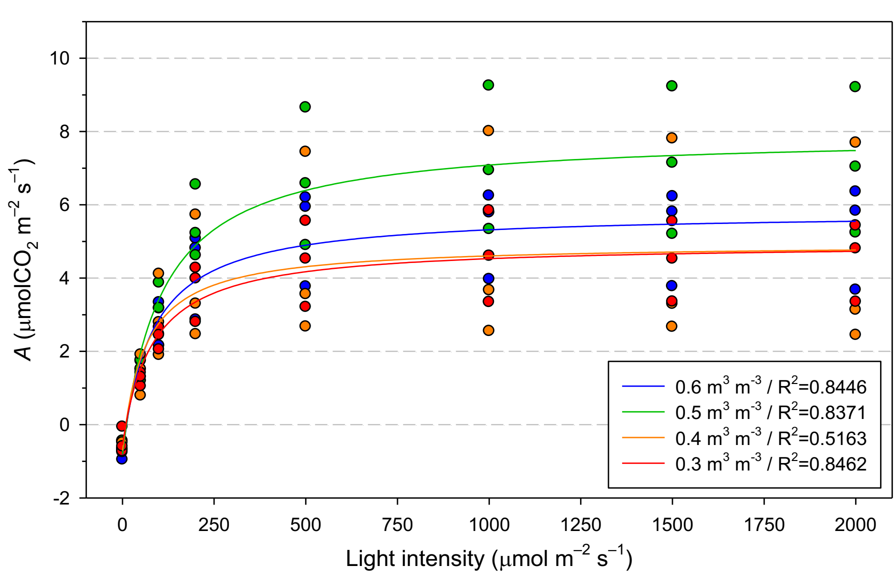

Fig. 4. Photosynthetic assimilation rate (A) with increasing light intensity after 12 weeks of cultivation periods as influenced by different volumetric water content levels in the pots (0.3, 0.4, 0.5, and 0.6 $m^3 \cdot m^{-3}$) in *Chrysanthemum naktongense* Nakai plants.

without significant reduction (Thorup-Kristensen and Kirkegaard 2016). In this experiment, soil moisture levels were maintained above a certain threshold, preventing severe stress on root development. Furthermore, because leaf and stem growth is generally more sensitive to water deficits than root growth, the significant differences observed in leaf and stem biomass, but not in root biomass, can be attributed to this differential sensitivity to soil moisture availability. Although root biomass did not exhibit statistically significant differences, its response trend was similar to that of the leaf and stem. This result suggests that both the shoot and root systems are influenced by varying soil moisture conditions. This growth behavior in response to soil moisture levels was consistent with the results of a previous study by Kiehl et al. (1992), who used a commercial *C.* cultivar. The decreased growth rate could be attributed to decreased photosynthetic ability in response to water stress (Fig. 4). Water stress can impede plant growth by limiting photosynthetic assimilation (Lipiec et al. 2013; Zlatev and Lidon 2012).

In greenhouses, growers can manipulate environmental factors to control and protect the crops. Understanding the effects of soil moisture levels on the growth of wild plants could be the first step in introducing plants for which management practices for greenhouse cultivation are not well known. Recent progress in smart farming has enabled data-based cultivation by integrating environmental and growth data collection (O'Grady and O'Hare 2017). Our objective was to develop a crop growth model for the stable production of *C. zawadskii* var. *latilobum* plants, and this study was a prerequisite for determining the parameters related to crop water requirements and efficient water management. Additionally, further studies on cultivation practices that consider other factors are required to increase growth rate and IWUE. Illustrating the growth performance by developing a crop growth model will further improve the productivity of this crop.

In summary, we observed the effects of different substrate moisture levels on the growth of *C. zawadskii* var. *latilobum*. The use of sensor-based automated irrigation systems successfully maintained the VWCs in pots. As the VWC levels decreased, leaf number, leaf area, and biomass significantly decreased. In this study, the 0.5 $m^3 \cdot m^{-3}$ treatment showed significant growth improvement and IWUE. The findings of this study will be useful for determining the water requirements and developing efficient irrigation techniques for cultivating this crop.

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