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Development of an Optimal Irrigation Control System Based on Transpiration Measurement in Soilless Culture of Paprika

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Development of an Optimal Irrigation Control System Based on Transpiration Measurement in Soilless Culture of Paprika

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ABSTRACT

Paprika is one of most profitable horticultural crop and classified as indeterminate-type plant which convert between vegetative and reproductive growth. It is known that those changes of growth type in paprika are influenced by various environmental factors and especially it has a close relationship with water management. Until now, irrigation methods based on accumulative radiation have been used for irrigation control in paprika cultivation. However a large amount of nutrient solutions could not be used by crops due to inaccurate irrigation control, especially at a large fluctuation of light intensity. In addition, the changes in substrate moisture content (MC) and electrical conductivity (EC) can s affect the transpiration in soilless culture, but there are a few results of the specified relationship among them. Thus, for improving crop productivity and efficiencies of water and fertilizers, optimum water management with precise irrigation control system and is required

The objectives of this study were to develop a presice irrigation control system that can monitor transpiration rate and control the moisture environments affecting plant growth, to establish irrigation control methods reflecting relathionships between plant water uptake and aerial or root-zone environmental factors, and finally to evaluate the developed systemfor applying to a large-scale commercial farm.

A precise irrigation control system was develoed, in which the transpiration rate was measured at 10 minute interval with less 5% error by using the change in plant weightwith load cells. The measured transpiration rate was more accutare than that estimated by an exsiting transpiration model. Plant response of water uptake to continuously changing environments could be more clarifiedby measuring transpiration at a shorter interval. Particularly, substrate MC, substrate EC, and drainage rate at each irrigation event could be controlled within target ranges in the system.

With the precise irrigatin control system, an optimum irrigation algorithm was developed for more accurate water management at various light intensities.Actual light intensity played an important role to cause the difference between actual transpiration and estimated transpiration with radiation accumulation , A modified irrigation control method (MIM) by compensating the light intensity could save a large amount of water compared to the conventional irrigation method (CIM) in summer season when a large fluctuation of light intensity occurs in Korea.

Transpiration amounts were precisely measured and analyzed with respect to root-zone environmental factors for investigating the relationship between them. The relationship between the range of substrate MC and EC increase could be clarified. From irrigation method using the relationship among root-zone environments to transpiration rate, fruit productivity and water use efficiency could be improved.

Compared with CIM, MIM was evaluated at a large-scale paprika commercial farm located in Hwasung, Korea. The root-zone environments were well controlled with good conditions for paprika cultivation in MIM. The water use efficiency and fruit production were 11 and 3.7% higher, respectively, in MIM than in CIM.

Form the results, it is concluded that the precisely-controlled irrigation system could clarify the relationship between transpiration rate and various environmental factors, and MIM could improve water use efficiency without negative effect on plant growth. In addition, this irrigation system will improve the crop productivity, to maintain environmental conservation, and to save cultuivation expense in soilless culture.

Keyword: environment control, fruit productivity, irrigation amount, irrigation interval, irrigation strategy, protected horticulture, solanaceae, transpiration, waste water

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GENERAL INTRODUCTION

Paprika is considered a valuable crop worldwide, and its yield and quality are essential factors for economic success. Due to its high sensitivity to ambient environments, paprika is generally cultivated in greenhouses where the microclimate can be precisely controlled (Ngouajio et al., 2008; Sezen et al., 2006). Particularly paprika is known as an indeterminate-type plant that can convert between vegetative and reproductive growth in response to environmental conditions. Among them, water condition is one of essential factors that determine growth type in paprika cultivation (Jones, 2004; Ngouajio et al., 2008; Sezen et al., 2006; Zotarelli, 2011). Because of the above reason, paprika is classified as being susceptible to soil water deficit (Smittle et al., 1994). To achieve high yield and quality of paprika fruits, an adequate irrigation strategy is essential for cultivation (Sezen et al., 2006; Shongwe et al., 2010; Singandhupe et al., 2003). Accordingly, transpiration rate is an important indicator for irrigation control and growth diagnosis in soilless culture of paprika.

As the water management is difficult in paprika cultivation because of various environmental conditions in different regions, it has been mainly conducted by grower's experience and conventional cultivation manuals (Pardossi and Incrocci, 2011; Tang et al., 2013). Therefore, the yield may be reduced due to drought or water excess caused by an under- or over-estimation of the transpiration rate (Ben-Gal et al., 2008; Ityel et al., 2012; Javot and Maurel, 2002; Letey et al., 2011). And also nutrient solutions may be wasted due to excessive use due to the same reason. For precise water management, a transpiration measurement with shorter interval is more favorable than the daily-based measurement which is conventionally applied for irrigation because it can reflect instantaneous plant response to ambient conditions.

Up to date, plant physiological studies and quantifications of the specific relationship between plant response and environmental conditions have been mostly conducted on aerial parts (Patane, 2011; Rao and Bhatt, 1988; Rogiers et al., 2011; Ta et al., 2011; Ta et al., 2012; Tai et al., 2010). Even for root-zone environmental factors, however, most of research have touched general relationships between each root-zone environmental factor and plant response, but not specific ones between root-zone environmental factors such as substrate EC and moisture content. In addition, no quantified data of momentary plant response to changing environmental factors were reported. The objectives of this study were to develop a precise irrigation control system that can monitor transpiration rate and control the moisture environments, to develop an accurate model to estimate transpiration rate with light intensity, to establish irrigation control methods reflecting relationships between plant water uptake and root-zone environmental factors, and finally to evaluate the developed system for applying to a large-scale commercial farm.

LITERATURE REVIEW

Precise Irrigation Control Methods in Soilless Culture

Paprika is known as an indeterminate-type plant that can convert between vegetative and reproductive growth in response to environmental conditions. Since water condition is one of important factors that determine the growth type in paprika cultivation (Jones, 2004; Ngouajio et al., 2008; Sezen et al., 2006; Zotarelli, 2011), various irrigation methods have been used for precise control of root-zone environments in paprika production (Jones, 2004; Locascio, 2005; Pardossi and Incrocci, 2011). Sensing the substrate moisture content is a typical method for measuring water consumption by plants (Bonachela et al., 2006a; Munoz-Carpena et al., 2005; Pardossi et al., 2009; St. Hilaire et al., 2003; Zotarelli, 2011). However, it requires many sensors and showed low accuracy especially in large-scale farms with unnecessary waste of water (Pardossi and Incrocci, 2011; Pardossi et al., 2009). Recently, an alternative irrigation methods based on drainage rate or plant weight change have been used for managing the plant drought stress (Fernández and Cuevas, 2010; Goldhamer and Fereres, 2001; Jones, 2004; Pardossi and Incrocci, 2011; Shelford et al., 2004). Although drainage control has been used for rinsing off the salt accumulation of substrate in a soilless culture system, the daily- based drainage rate control caused continuous increase in substrate EC during growing period. The imbalance of drainage during the day can cause large changes in the root-zone environment and is closely related to plant stress. In addition, irrigation methods through the direct measurement of water flow in plant have been attempted to make precise irrigation strategy (Conejero et al., 2007; Pertierra et al., 2002). However, it requires not only expensive precision sensors such a sap flow but also experts to deal with these measurement instruments. Therefore, this irrigation method has many limitations of application in cultivation.

Estimation of Transpiration Amount for Irrigation Control

Irrigation strategies can be determined by calculating the transpiration amount of plants using various transpiration models (Jolliet, 1994; Jolliet and Bailey, 1992; Medrano et al., 2005; Ta et al., 2011). So far, the estimated transpiration amount has been used to determine the irrigation amount and irrigation interval in many paprika cultivations (Allen and Fisher, 1990). To estimate the transpiration rate, the daily accumulated radiation were calculated from the sum of the photons that reached a unit area over a certain time (Bryla et al., 2010; Gadissa and Chemeda, 2009; Gercek et al., 2009). In general, a modified Penman-Monteith's equation incorporating radiation (RAD), leaf area index (LAI), and vapor pressure deficit (VPD) has been widely used for estimating the transpiration amount (Jolliet, 1994; Jolliet and Bailey, 1992; Medrano et al., 2005; Ta et al., 2011b). Particularly the transpiration rate increased with light intensity (Kim et al., 2011; Kuiper, 1961; Saez et al., 2012), crop growth stage, and development (Jolliet and Bailey, 1992; Medrano et al., 2005). Among various environmental factors, the transpiration rate was mostly affected by light intensity (Fernandez and Cuevas, 2010; Guttormsen, 1974; Shani et al., 2007) and known as increasing in proportion to light intensity.

However recent researches reported that the light intensity and transpiration rate do not have a linear relationship (Ali et al., 2009; Anderson et al., 2000; Green, 1993; Rahimikhoob et al., 2012). At a high light intensity condition, temperature also rises, and it alters vapor pressure deficit (VPD) condition in greenhouse (Aubinet et al., 1989; Medrano et al., 2005). And it causes the stomata of plants closed during the times of high light intensity, and the transpiration rate tends to decrease at these times (Del Amor et al., 2010; González-Dugo et al., 2007; Kuiper, 1961).

As above, estimating transpiration amount on a day-to-day basis can make errors because of the ever-changing environments. Therefore, more accurate transpiration calculation considering instantaneous plant response is needed for precise irrigation control.

Environmental Factors Affecting Transpiration

Transpiration rate becomes important indicators for not only growth diagnosis but irrigation strategy in soilless culture of paprika. There were many studies on environmental control for improving transpiration amount because the transpiration is mainly affected by various environment factors in aerial or root-zone parts.

Aerial environment factors

Many researches on the transpiration response to aerial environment factors have been conducted. The transpiration rate increased with increasing light intensity (Inoue, 1980; Janes, 1970). Stomata opened under high light intensity but did not respond to high leaf temperature (Nobuoka et al., 1996). However, high leaf temperature increased the transpiration rate with increasing light intensity which is attributed to the increased vapor pressure deficit in the boundary layer of the leaf. And temperature and relative humidity related to VPD also affected transpiration. Under high relative humidity, winds decreased the transpiration rates with increasing light intensity. On the other hand, under low relative humidity, winds increased the transpiration rates in tomato crop (Nobuoka et al., 1997). Tartachnyk and Blanke (2007) showed a transpiration response to a combination of light intensity and CO2 concentration, where dark respiration and transpiration were negligibly affected by increasing CO2 concentrations from 600 to 900 ppm under low light conditions. In addition, Clum (1926) and Downes (1970) reported the transpiration could be influenced by a combination of environmental factors such light intensity, VPD, and CO2.

Optimum ranges of environmental conditions such as VPD and light intensity, CO2, plant density, and irrigation strategy that can maximize the transpiration have been studied, and appropriate irrigation methods have been proposed (Patane, 2011; Rao and Bhatt, 1988; Rogiers et al., 2011; Ta et al., 2011a; Ta et al., 2012; Tai et al., 2010).

Root-zone environment factors

Few studies were reported on the transpiration response to root-zone environment compared to those to aerial environments. Transpiration was affected by root-zone environment such as substrate EC and MC (Gong et al., 2005; Kang et al., 2003; Li et al., 2013; Li et al., 2002). Havrda et al. (1989)

and Nesmith et al. (1992) reported the relationship between substrate moisture content (MC) control and substrate EC change. Generally, it is known that substrate MC has an inverse relationship to substrate EC. The EC showed a decrease with increasing water content, as the fertilizer ions in the pore water become more diluted as volumetric water content increases (Scoggins and van Iersel, 2006). Nagy et al. (2013) and Stamm (1930) have ever used the above relationship for estimating substrate MC and EC at several types of media. The substrate EC change was slower than substrate MC change in actual soilless cultivation. Thus, control of substrate EC was not easy like that of substrate MC. Therefore, method of substrate MC control by irrigation strategy has been used for optimizing root-zone environment in soilless culture. In general, water uptake by plants is more influenced by substrate EC than substrate MC. Charbonneau et al. (1988), Dorais et al. (2001), and VanIeperen (1996) explained that the increase in substrate EC could act as drought stress to plants in soilless culture of tomato.

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CHAPTER Ⅰ

Development of a Real-time Irrigation Control System Considering Transpiration, Substrate Electrical Conductivity, and Drainage Rate of Nutrient Solution in Soilless Culture of Paprika

ABSTRACT

As paprika plants change their growth state between vegetative and reproductive significantly correlated with water stress, an appropriate management of irrigation for the plant growth is essential. A finely-controlled system for continuously measuring the transpiration amount and root-zone environments was required. The objectives of this study were to develop an irrigation control system for accurate monitoring of water consumption by the plants, to control root-zone environment conditions such as drainage rate and electrical conductivity (EC) in substrate, and to compare the estimated transpiration amount by model and the measured one with the developed system. Environmental factors, such as light intensity, temperature, humidity, and EC of nutrient solution were measured. Accumulated radiation was used as a basic index for irrigation control. A precise irrigation control system which can real-time monitor the aerial and root-zone environment factors and control the irrigation amount and interval was developed. Drainage rate and substrate EC were well controlled in the developed system. Transpiration amount could be more accurately calculated with the system than by estimation with transpiration model. Particularly, adequate amount of water could be supplied required for optimum plant growth by considering multi variables such as accumulated radiation, drainage rate, and substrate EC. By using the system, systemized irrigation strategies can be established and the more efficient irrigation management can be possible.

Additional keywords: Irrigation frequency, solar radiation, transpiration monitoring system

INTRODUCTION

Paprika is considered a valuable crop worldwide, and its yield and quality are essential factors for economic success. Due to its high sensitivity to ambient environments, paprika is generally grown in greenhouses where the microclimate can be precisely controlled (Ngouajio et al., 2008; Sezen et al., 2006). Importantly, paprika is known as indeterminate-type plant that can convert between vegetative and reproductive growth in response to environmental conditions. Therefore the water condition of the root medium is one of the most important factors that determine the growth type in paprika cultivation (Jones, 2004; Ngouajio et al., 2008; Sezen et al., 2006; Zotarelli, 2011). For this reason, the paprika plant is classified as being susceptible to soil water deficit (Smittle et al., 1994). To achieve a stable production of paprika with high yield and quality, an adequate irrigation control is essential.

For the purpose of precise moisture control, various irrigation methods have been used for horticultural crop production (Jones, 2004; Locascio, 2005; Pardossi and Incrocci, 2011). Development of transpiration models were most important approaches for establishing irrigation strategies and, among them, a modified Penman-Monteith's evapotranspiration model incorporating radiation (RAD), leaf area index (LAI), and vapor pressure deficit (VPD) had been dominantly applied (Jolliet, 1994; Jolliet and Bailey, 1992; Medrano et al., 2005; Ta et al., 2011). However, transpiration amount was not always accurately estimated depending on plant cultivars and environmental factors. In addition, a direct sensing of the moisture content of substrate also has been tried for irrigation control (Bonachela et al., 2006; Munoz-Carpena et al., 2005; Pardossi et al., 2009; St. Hilaire et al., 2003; Zotarelli, 2011). However, it required many sensors and showed low accuracy in a large-scale farm, thereby creating unnecessary waste of water (Pardossi and Incrocci, 2011; Pardossi et al., 2009).

Recently, irrigation methods based on drainage rate or the change in plant weight have been used for management of plant drought stress (Fernández and Cuevas, 2010; Goldhamer and Fereres, 2001; Jones, 2004; Pardossi and Incrocci, 2011; Shelford et al., 2004). As the imbalance of drainage during the day can cause an undesirable phenomenon like salt accumulation in substrate and lead to plant stress. Therefore, for better plant growth, the water amounts required by plants and the root-zone environmental conditions should be monitored, and the irrigation and drainage rate should be finely controlled. Kim et al. (2011) and Reddy (1994) developed irrigation control systems considering drainage amount as single variable, but did not monitor the plant growth with the systems.

The objectives of this study were to develop an irrigation control system for accurate monitoring of water consumption by paprika plants, to control root-zone environment conditions such as drainage rate and electrical conductivity (EC) in substrate, and to compare the estimated transpiration amount by model and the measured one with the developed system.

MATERIALS AND METHODS

Configuration of the System

The irrigation control system is illustrated in Fig. Ⅰ-1. The dimensions of the frame were 1.2 (L) x 1.2 (W) x 2.8 m (H) with two gutters, held by two weighing sensors, having a size of 1 (L) x 0.2 (W) x 0.1 m (H) connected to a drainage tube. Two collectors, each with a weighing sensor were installed to measure the amount of irrigation and drainage at the bottom of the system. The weights of substrates with plants, and the amounts of irrigation or drainage, were measured by weighing sensors (JSB-50 and JSB-20, CAS Co., Ltd., Yangju, Korea) with resolution of 1 g and 0.1% accuracy of full scale.

Environmental factors, such as radiation, temperature, relative humidity, substrate EC and moisture content, and drainage EC and pH, were recorded every 5 sec by a datalogger (CR1000, Campbell Scientific, Logan, UT, USA) from the following sensors: solar radiation [pyranosensor (SP-110-L10, Apogee Instruments, Inc., Logan, UT, USA)], temperature (CS220, Campbell Scientific, UT, USA), and relative humidity (PCMini70, Gilwoo Trading Co., Ltd., Seoul, Korea). Temperature and EC of the nutrient solution and substrate, and moisture content of the substrate, were measured using a multiple sensor [WT1000B Frequency Domain Reflectometry (FDR), Mi-Rae Sensor Co., Ltd., Seoul, Korea] located between two plants at the two-third position of the slab. An EC sensor (DCF-1, DIK electronics, Bucheon, Korea) and a pH sensor (DPH-1, DIK electronics, Bucheon, Korea) were installed in the middle of the drainage tube. A pump (PUN-350M, Wilo-Pump Co., Ltd., Ansan, Korea) was attached to each system for drip irrigation with a flow rate of 30 mL·min-1 per dripper and was operated by the irrigation set. The system allowed the user to set the optimum range of substrate EC according to plant growth stage and cultivar. In total, three irrigation control systems were assembled and used in this experiment.

Crop Cultivation and Experimental Conditions

This experiment was performed in a venlo-type glasshouse located at the Experimental Farm of Seoul National University (Suwon, Korea, lat. 37.3°N, long. 127.0°E). The vents on the roof and sidewall were automatically opened when the temperature was higher than 26°C during the day. Paprika seedlings (*Capsicum annuum* L. 'Fiesta') at 60 days post-sowing on rockwool media (Grotop, Grodan, Roermond, Netherlands) in a commercial farm (Pyeongchang, Korea) were used for the experiment. On March 28th, 2012, after 2 weeks of acclimatization to the subirrigation system at a nutrient concentration of 2.0 $dS \cdot m^{-1}$, the paprika seedlings with 5-6 nodes were transplanted into 0.9 (L) x 0.15 (W) x 0.07 m (H) rockwool slabs (MaXXima, Cultilène, Tilburg, Netherlands) and placed in the gutters with a plant density of 3 plants/m^2. Experimental treatments were applied for 170 days from transplanting. There were two slabs for each system, and 18 total plants were used for this experiment. The EC and pH ranges in the nutrient solution were 2.6-3.0 $dS \cdot m^{-1}$ and 5.5-6.5, respectively. The plants were pruned to maintain two main stems, which were vertically trellised to a 'V' canopy system (Jovicich et al., 2004).

System Monitoring and Operation

Data for irrigation control were wirelessly collected by the datalogger every 5 sec (ZigBee wireless signal format), transmitted to a main control computer, and automatically stored every 10 sec. The transpiration amount, Tr, was calculated using the following equation at 60-sec intervals:

$$Tr = \Delta P - \Delta(Ir - Dr) \qquad \text{(Eq. I-1)}$$

where Tr, Ir, Dr, and ΔP mean transpiration amount (g), irrigation amount (g), drainage amount (G), and the decrease in the weights of plant and substrate (g). Weight changes by pruning were excluded from transpiration calculation. And evaporation from substrate was ignored, because it was a very small amount less than 0.5% of transpiration amount. To compare the measured transpiration of paprika plants, estimated transpiration using environmental factors was expressed by following modified transpiration model (TA et al., 2011):

$$Tr = a * [1 - \exp(-k * LAI)] * RAD + b * LAI * VPD \qquad \text{(Eq. I-2)}$$

where LAI, RAD, and VPD mean leaf area index ($m^2 \cdot m^{-2}$), radiation amount ($W \cdot m^{-2}$), and vapor pressure deficit, respectively. The coefficients a, b, and k were $9.55 * e^{-4}$, 0.03 ($kg \cdot d^{-1}$), and 0.84, respectively. While VPD was not included in this model, Ta et al. (2011) confirmed the close relationship between the daily transpiration of paprika plants with RAD and LAI. This correlation exists because the majority of transpiration occurs during the daytime. The values of the parameters used for estimating the transpiration rate in Eq. 2 were obtained from the result of (TA et al., 2011).

Drainage rate was continuously calculated from the amounts of irrigation and drainage. Irrigation frequency and the total irrigation amount were calculated by counting the pump operation and accumulated operating time of pump, respectively. Water amounts used by plants were calculated from the total transpiration amount divided by the irrigation amount for a day. Leaf area was calculated using a leaf area equation which considers leaf length and width measurements (Park et al., 2009). The variation of substrate EC was monitored, and these measured data were used to control irrigation. Irrigation pumps were operated based on cumulative radiation and set values for moisture content or substrate EC. The irrigation control was programmed to be able to prioritize among the above conditions to determine irrigation frequency and amounts. Graph module analysis from the collected data was performed using SigmaPlot 13 (Systat software Inc., CA, USA).

Experimental Irrigation Treatments

To examine the irrigation operation, three operation conditions were used (Table. Ⅰ-1). In system 1, a conventional irrigation started when radiation accumulation reached every 100 $J \cdot cm^{-2}$, at which point, 150 mL of nutrient solution was supplied to each plant at each irrigation event (Hellemans, 2006).

Since drainage rate of 30% during the day was recommended for preventing salt accumulation in substrate (Hellemans, 2006), in system 2, irrigation was initially the same as in system 1 but stopped when the drainage rate reached 30% at every irrigation event. The additional factor of substrate EC was programmed into system 3 and based on system 2. Although accumulated radiation remained lower than set point of 100 $J \cdot cm^{-2}$, when substrate EC exceeded 3.8 $dS \cdot m^{-1}$ [according to paprika growing manual (Hellemans, 2006)], irrigation started to flush the salinity out of the substrate. In this case, the irrigation was programmed to stop when substrate EC decreased to less than 3.5 $dS \cdot m^{-1}$ (90% of substrate EC set for irrigation). The drainage rate of each event and the total number of daily drainage events were compared among all irrigation treatments. The fluctuation of substrate EC in system 3 was compared with that in systems 1 and 2 to determine the performance of the irrigation system during experimental periods.

RESULTS AND DISCUSSION

Consecutive Measurements of Transpiration

Fig. Ⅰ-2 shows sample results under the irrigation based on drainage rate (system 2). Climate and root-zone environmental data, as well as weight data for transpiration calculation were collected every 5 sec during experimental periods. Cumulative radiation amount, drainage rate, irrigation frequency, irrigation amount at each irrigation event, and transpiration amount was calculated from the measured data in Fig. Ⅰ-2 (Fig. Ⅰ-3). Fig. Ⅰ-3-B shows that the drainage rate was well controlled at approximately 30% for all irrigation events in system 2.

The estimated amount of accumulated transpiration using Eq. Ⅰ-2 and the calculated one using Eq. Ⅰ-1 in systems 2 were compared at an interval of 10 min (Fig. Ⅰ-4-A) during experimental periods. Fig. Ⅰ-4-A shows that the amount of daily accumulated transpiration in system 2 were around 15% higher than that estimated by Eq. Ⅰ-2. However, despite of an increase in LAI, the difference between estimated and measured transpiration amounts were not significant at the end of the experiment because of low light intensity during rainy season especially in summer. In all three irrigation systems, the measured amounts of accumulated transpiration were higher than those of estimated one during experimental periods (Fig. Ⅰ-4-B). The maximum 18% differences between measured and estimated transpiration amounts were observed in system 3 at the end of the experiment. The lower transpiration amount in system 1 compared to those in systems 2 and 3 is presumably because the plants in system 1 have induced water stress from the increase in substrate EC (due to insufficient water supply), as shown in Fig. Ⅰ-5. Water stress by increased substrate EC is one of the major factors that interfere with transpiration in plants (Zotarelli et al., 2009).

The cumulated radiation amount, VPD, and LAI were commonly used as variables in Eq. Ⅰ-2. However, transpiration can also be influenced by other factors, such as air flow, shading by greenhouse structures, concentration of carbon dioxide, root-zone environmental conditions, and various cultivars (Hellemans, 2006; Smeal et al., 1991). These environment factors continuously change the coefficients of the transpiration equation and can create errors. These errors can be reduced by calculating the transpiration amount by weighing data rather than estimating with the predetermined equation. The continuance of measurement is the main difference between the two methods, and can reduce the estimation errors in transpiration under different environmental conditions.

Function of the Drainage Rate Control at each Irrigation Event

The drainage rate was monitored and controlled close to the set value at each irrigation event. Table Ⅰ-2 showed a detail comparison of drainage rate at every irrigation event from 168 DAT to 170 DAT as a sample case in summer. When the conventional irrigation method based on an accumulated radiation of 100 $J \cdot cm^{-2}$ was applied, as in system 1, more than 70% of the drainage was concentrated after 12:00 pm (from the 3rd irrigation event) because drainage almost did not occur at the 1st irrigation event. However, in system 2 a drainage rate of 30% was maintained at every event under the irrigation control. Although the distribution of drainage rate varied more in system 3 compared with system 2, drainage was not concentrated at a certain time of the day as shown in system 1. The drainage rate in system 3 was highest at first irrigation event of the day for salinity rinsing in substrate. In addition, the first irrigation event during the day was supplied at the earliest time in system 3 among the treatments. Since it was possible to control substrate EC at earlier irrigation events in system 3, there was no difference in the number of irrigation event. In fact, drainage control is closely related not only to the amount of water supply for plants but also to the change in substrate EC (Scoggins and van Iersel, 2006). The more moisture content and substrate EC changed, the more plants received stress. Although the rapid increase in substrate EC could be prevented by rinsing out the substrate with fresh nutrient solution, this process consumes a large amount of water. Therefore, maintaining regular drainage can decrease the waste of water through excessive irrigation and avoid the drought stress of plants in soilless culture systems.

Function of the Substrate EC Control and Efficiency of Water Usage

The substrate EC showed a wide range of fluctuation during the experiment in system 1, ranging from 2.54 to 5.50 $dS \cdot m^{-1}$, while gradually increased to 4.49 $dS \cdot m^{-1}$ in system 2 and maintained within the set range of 2.67 to 3.90 $dS \cdot m^{-1}$

in system 3 (Fig. Ⅰ-5). Considering that substrate EC is closely related to transpiration amount and substrate moisture content, the rapid increase in substrate EC in system 1 is likely due to insufficient water supply, especially in the morning and the increased substrate EC in system 2 could be due to insufficient drainage amount compared with the transpiration amount. Therefore, it was assumed that a drainage-based irrigation control with management of substrate EC could supply sufficient water to meet transpiration. In other word, the plant drought stress could be more effectively prevented by adding the management function of substrate EC than by using only drainage-based irrigation method.

Approximately 92.5 kg of water was used for irrigation of a plant in the system 1 during the experimental period. Alternatively, 105.9 and 117.82 kg of water were used in systems 2 and 3, respectively, and 24.8, 32.0, and 41.9 kg of drainage occurred in system 1, 2, and 3, respectively (Table Ⅰ-3). From the above data, the efficiencies of water usage by the paprika plants were calculated as 72.3%, 69.2%, and 63.8% in system 1, 2, and 3, respectively (Table Ⅰ-3). The efficiency of water use was the highest in the conventional irrigation method (system 1), most likely because the water supply was insufficient compared with the transpiration amount. Then it caused drought stress on the plant by rapid increase in substrate EC. Although the water use efficiency was the lowest in system 3 among all the systems, the substrate EC remained constant but the amount of transpiration in system 3 was approximately 13% greater than that in system 1 (Fig. Ⅰ-4-B).

From the results, it was considered that the transpiration amount was most likely increased under sufficient water supply and stable control of root-zone environment. Abu-Awwad (1998) and Hati et al. (2001) reported that the management of substrate EC through sufficient water supply increased transpiration amount from vegetable crops. In addition, the total leaf number increased while leaf area decreased with increase of substrate EC from insufficient water supply. And it reduced transpiration and caused plant physiological disorder (Li and Stanghellini, 2001). In this study, the substrate EC could be precisely controlled by increasing irrigation events in system 3, however, this method also led to a significant increase in water consumption. For preventing excessive water use and improving fruit productivity, an optimum range of substrate EC through irrigation control should be investigated in soilless cultivation of paprika.

System Operation

Over the course of this experiment, the irrigation was controlled by consecutive monitoring of environmental and substrate conditions as a determinant of irrigation. Irrigation event could start based on set substrate EC, substrate moisture content (MC) and accumulated radiation, and the irrigation amount at each event could be determined by substrate EC, MC, irrigation amount, and drainage rate (Fig. Ⅰ-6). And initial values, priority, and the items of the criteria for optimal irrigation management could be set before operation. Continuously measured transpiration data was used to set these initial values and priority, and to identify the water movement in plants for adequate irrigation. The data in system 2 in Table Ⅰ-2 showed that drainage rate was controlled to fit the set value. And also the function of substrate EC control to avoid water stress was well-defined (Fig. Ⅰ-5). The radical change of root-zone environment could be controlled by the irrigation management with a measurement of transpiration in this system. Furthermore, unnecessary water loss and plant stress could be reduced by applying an adequate irrigation strategy. Until now, researches on irrigation system focused on single variable like drainage (Kim et al., 2011; Reddy, 1994). However, more precise irrigation control could be available considering the combination of variables like accumulated radiation, drainage rate, and substrate EC with this system.

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Table Ⅰ-1. Treatments for three irrigation control strategy.

System No.	Irrigation-on	Irrigation-off
1	Accumulated radiation (every 100 J·cm^{-2})	150 mL/dripper/event
2	Accumulated radiation (every 100 J·cm^{-2})	Drainage rate of 30%
3	Accumulated radiation (every 100 J·cm^{-2})	Drainage rate of 30%
	Substrate EC > 3.8 dS·m^{-1}	Substrate EC < 3.5 dS·m^{-1}

Table Ⅰ-2. Comparisons of irrigation, drainage amounts and drainage rates at different irrigation control systems (168-170 DAT, days after transplanting).

Irrigation event		System 1[z]			System 2			System 3		
		Irrigation amount (kg/6 plants)	Drainage amount (kg/6 plants)	Drainage rate (%)	Irrigation amount (kg/6 plants)	Drainage amount (kg/6 plants)	Drainage rate (%)	Irrigation amount (kg/6 plants)	Drainage amount (kg/6 plants)	Drainage rate (%)
168 DAT	1	0.915	0.000	0.0	2.532	0.766	30.3	1.775	0.925	52.1
	2	0.906	0.347	38.3	0.774	0.240	31.0	1.366	0.485	35.5
	3	0.930	0.275	29.5	0.876	0.270	30.8	1.349	0.502	37.2
	4	0.924	0.326	35.2	0.810	0.253	31.2	1.001	0.320	32.0
	5	0.915	0.372	40.6	0.690	0.221	32.0	0.891	0.279	31.3
	6	0.921	0.155	16.9	1.374	0.419	30.5	0.336	0.239	71.1
	7							0.715	0.217	30.3
	8							0.565	0.185	32.7
Sum		5.511	1.474		7.056	2.169		7.999	3.152	
Average				26.8			30.7			39.4
169 DAT	1	0.903	0.000	0.0	3.006	0.910	30.3	1.950	0.942	48.3
	2	0.912	0.313	34.3	0.810	0.252	31.1	1.386	0.521	37.6
	3	0.912	0.295	32.3	1.092	0.335	30.7	1.356	0.423	31.2
	4	0.927	0.272	29.3	1.098	0.342	31.1	0.683	0.271	39.7
	5	0.909	0.221	24.3	1.410	0.429	30.4	1.596	0.509	31.9
	6							0.698	0.211	30.2
Sum		4.563	1.100		7.416	2.268		7.668	2.877	
Average				24.1			30.6			37.5
170 DAT	1	0.933	0.000	0.0	2.880	0.882	30.6	2.382	1.265	53.1
	2	0.906	0.303	33.4	0.810	0.258	31.9	1.501	0.548	36.5
	3	0.909	0.277	30.5	0.990	0.312	31.5	1.234	0.417	33.8
	4	0.906	0.291	32.1	1.218	0.378	31.0	0.316	0.145	45.9
	5	0.921	0.186	20.2	1.614	0.495	30.7	1.298	0.496	38.2
	6							0.988	0.301	30.5
Sum		4.575	1.057		7.512	2.325		7.720	3.172	
Average				23.1			31.0			41.1

[z] See Table Ⅰ-1.

Table Ⅰ-3. Comparisons of accumulated irrigation, drainage, and transpiration amount and water use efficiency of paprika growth at different irrigation control systems (1-170 DAT, days after transplanting).

System No.	Accumulated			Water use efficiency (%)
	Irrigation (kg/plant)	Drainage (kg/plant)	Transpiration (kg/plant)	
1[z]	92.49	24.78	66.87	72.3
2	105.87	31.98	73.26	69.2
3	117.82	41.85	75.17	63.8

[z] See Table Ⅰ-1.

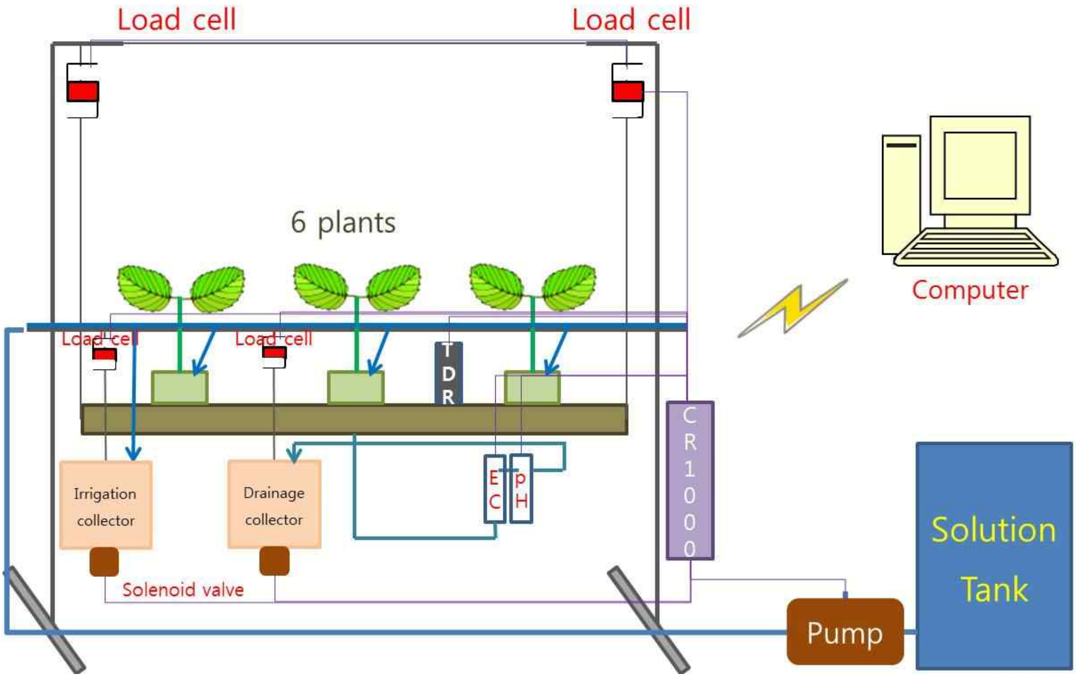

Fig. Ⅰ-1. A schematic diagram of the irrigation control system used in this study.

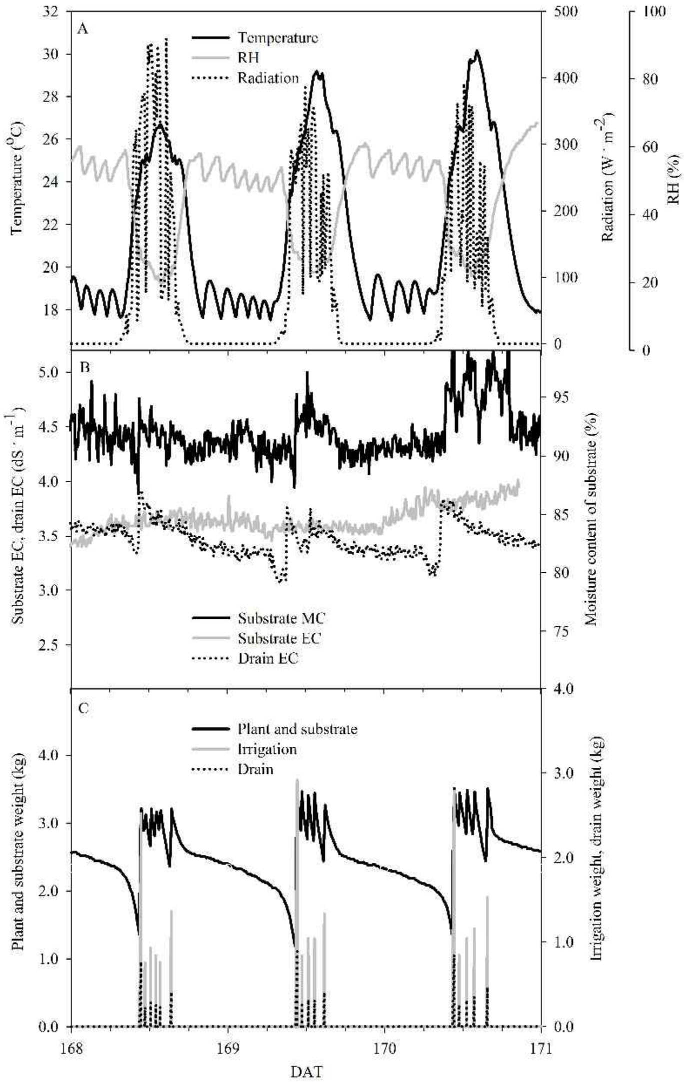

Fig. Ⅰ-2. Environments (A; temperature, relative humidity, and radiation), moisture content and ECs (B; moisture content, substrate EC, and drainage EC), and weights (C; irrigation amount, drainage amount, and weight change of plant and substrate) measured in the system 2 (168-170 DAT, days after transplanting).

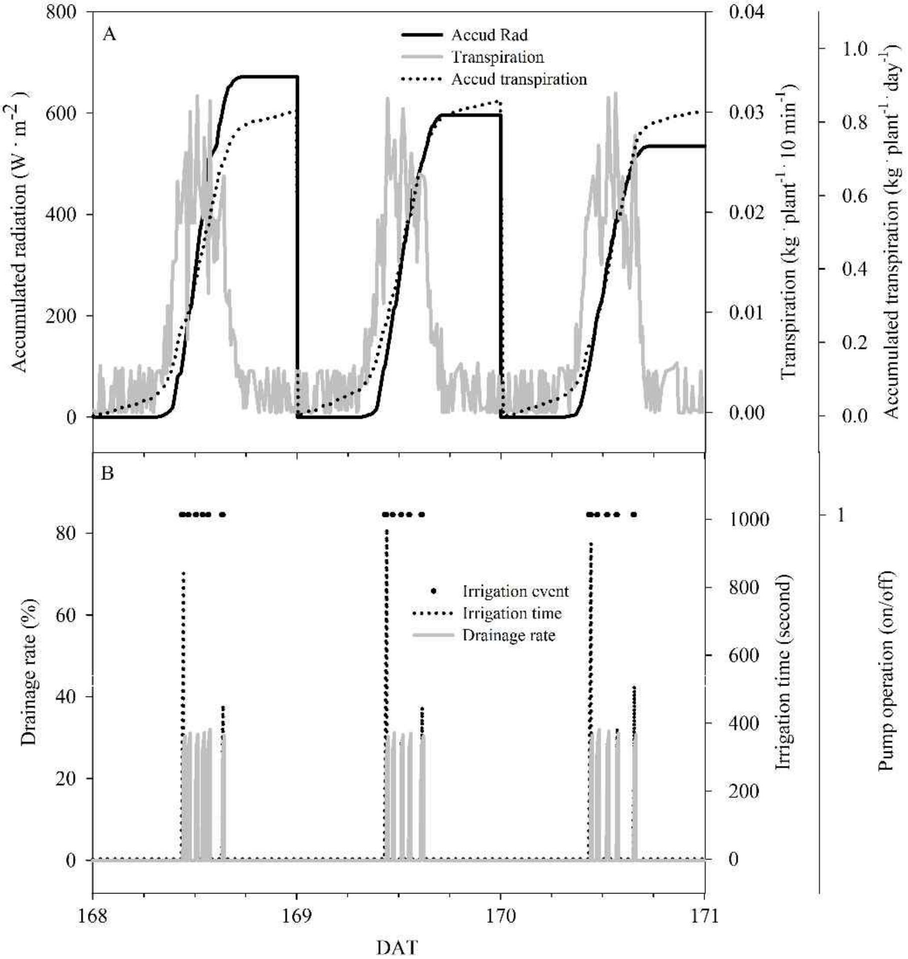

Fig. Ⅰ-3. Calculated transpiration, accumulated radiation and accumulated transpiration (A), and drainage rate, pump operation, and irrigation time (B), in the system 2 (168-170 DAT, days after transplanting).

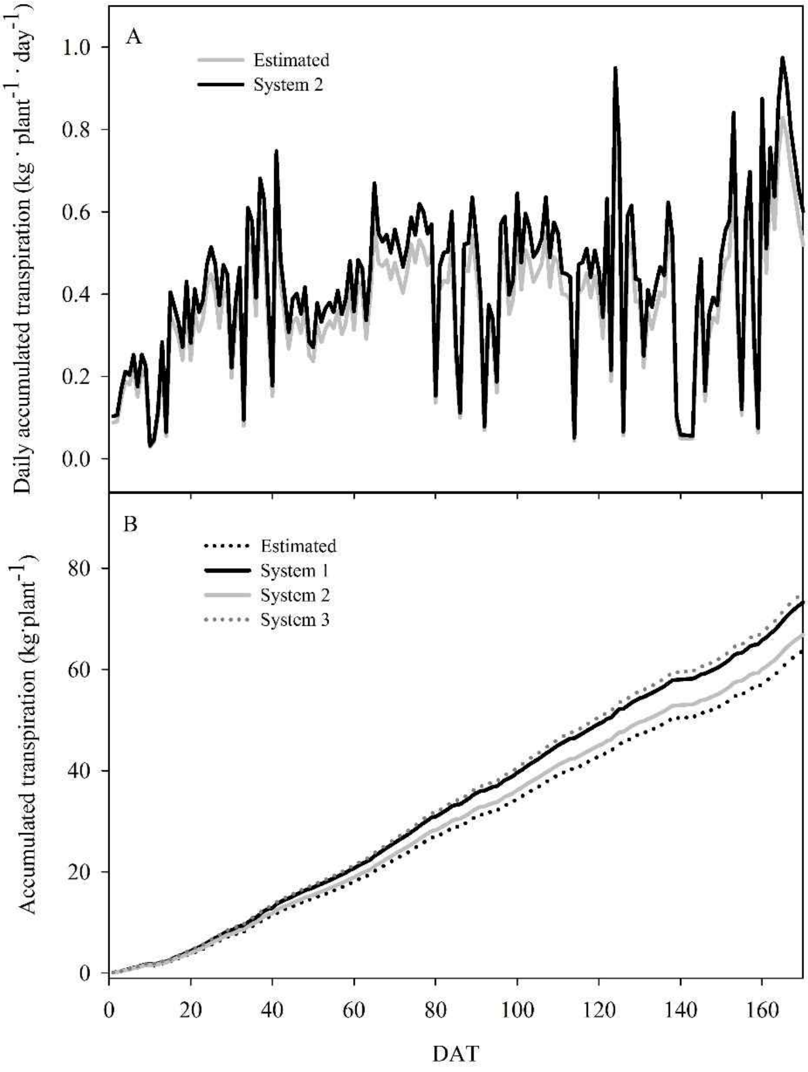

Fig. Ⅰ-4. Comparisons of the transpiration amount estimated by transpiration model and obtained with the system 2 (A), and the daily accumulated transpiration amount for experimental period (1-170 DAT, days after transplanting) (B).

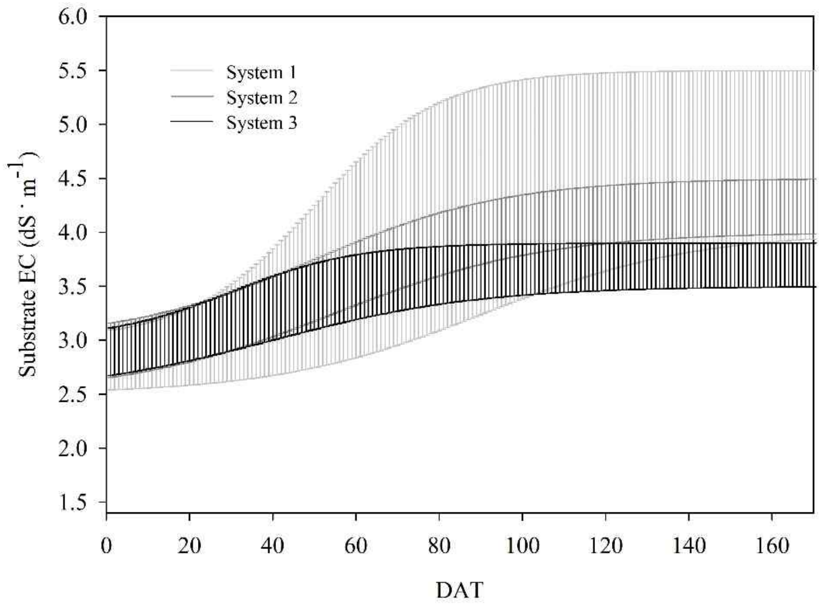

Fig. Ⅰ-5. Comparison of substrate EC among the systems 1, 2, and 3 during experimental period (1-170 DAT, days after transplanting).

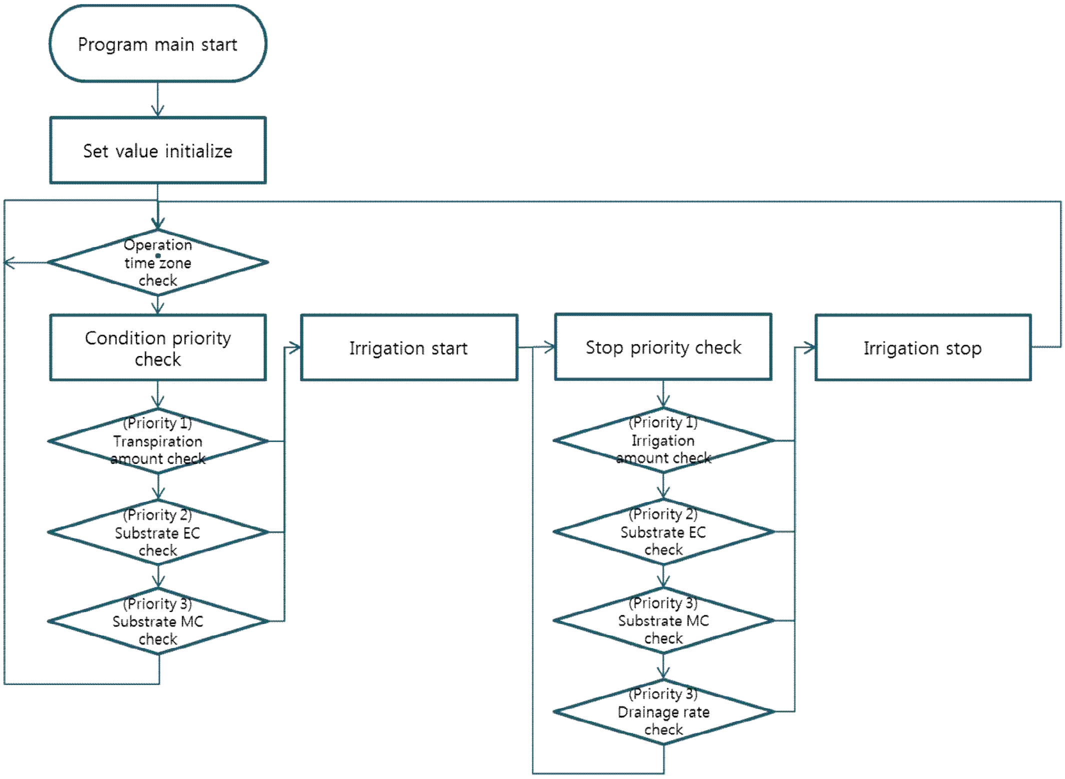

Fig. Ⅰ-6. Flowchart of an irrigation control.

CHAPTER Ⅱ

Estimating the Actual Transpiration Rate with Compensated Levels of Accumulated Radiation for the Efficient Irrigation of Soilless Cultures of Paprika

ABSTRACT

Water management directly affects the productivity of paprika plants and is currently determined based on accumulated radiation levels. However, the amount of water used by the plants does not always increase proportionally to the accumulated radiation levels. Thus, relationship between light intensity and transpiration rate in the short-term needed to be analyzed for more efficient irrigation strategy. In this study, a sigmoidal relationship was observed between light intensity and transpiration rate at an interval of 10 min using a consecutive transpiration monitoring system. From this relationship, a compensated equation was developed that can calibrate the light intensity. When a modified irrigation was applied using this compensated equation, less water was used compared to a conventional irrigation that supplies water proportional to accumulated radiation, especially in summer. Moreover, there was no significant difference in the transpiration rates and plant growth between plants watered with either the conventional or modified with compensated equation irrigation method. From these results, it was concluded that water was used more efficiently with the modified irrigation method without affecting plant growth.

Additional keywords: irrigation method, solar radiation, transpiration estimation, water absorption

INTRODUCTION

Paprika is one of the most profitable horticulture crops. Given that paprika productivity is closely related to irrigation management (Sezen et al., 2006; Shongwe et al., 2010), improving the efficiency of water and nutrient use with adequate water management is critical for reducing the cost of paprika cultivation (Singandhupe et al., 2003). The approximate rate of transpiration is commonly used to estimate the amount of water that is supplied during paprika cultivation (Allen and Fisher, 1990). The transpiration rate is mostly affected by light intensity in addition to other environmental factors (Fernandez and Cuevas, 2010; Guttormsen, 1974; Shani et al., 2007). Particularly transpiration increases with light intensity (Kim et al., 2011; Kuiper, 1961; Saez et al., 2012), crop growth stage, and development (Jolliet and Bailey, 1992; Medrano et al., 2005).

In most cases of paprika cultivation, irrigation management practices are based on the estimated transpiration amount, which is determined by the levels of accumulated radiation (De Pascale et al., 2011; Qiu et al., 2011; Shao et al., 2010; Ta et al., 2011b; Ta et al., 2012). In general, to estimate transpiration rates, the levels of radiation accumulated daily are calculated from the sum of the photons that reach a defined area over a certain unit of time (Bryla et al., 2010; Gadissa and Chemeda, 2009; Gercek et al., 2009). In soilless culture, a conventional irrigation method supplies water proportional to accumulated radiation. However, changes in light intensity that occur during the day are ignored in these calculations. In fact, the light intensity and transpiration rate do not have a linear relationship (Ali et al., 2009; Anderson et al., 2000; Green, 1993; Rahimikhoob et al., 2012). At high light intensity condition, temperature also rises, and it alters vapor pressure deficit (VPD) condition in a greenhouse (Aubinet et al., 1989; Medrano et al., 2005). And it causes the stomata of plants closed during times of high light intensity, and the transpiration rate tends to decrease at these times (Del Amor et al., 2010; González-Dugo et al., 2007; Kuiper, 1961). For this reason, conventional irrigation method using a linear equation to determine the levels of accumulated radiation can cause errors in estimating the amount of water used by plants, especially under high light conditions.

The light intensity fluctuates during the day at different rates depending on the region, latitude, and season (Agele et al., 2006), thus, errors in transpiration estimation will be larger when there are large fluctuations in light intensity during the day (Sinoquet et al., 2001). For these reasons, the yield may be reduced due to drought or water excess caused by an under- or over-estimation of the transpiration rate (Ben-Gal et al., 2008; Ityel et al., 2012; Javot and Maurel, 2002; Letey et al., 2011), and nutrient solutions may be wasted due to excessive use because of an overestimation of the transpiration rate. For reduction of the overestimated irrigation amount, instantaneous transpiration with shorter interval is more favorable instead of daily accumulated one conventionally applied for irrigation. The shorter the measurement interval is, the higher the measurement accuracy becomes by reflecting real plant response to ambient conditions.

In this study, a modified irrigation method that better estimates transpiration rates by compensating for varying light intensities and radiation accumulation was developed with a precise irrigation monitoring and control system. It was subsequently compared in water use efficiency by plant irrigation systems controlled with our compensated equation or with conventional irrigation in summer and winter.

MATERIALS AND METHODS

Growing Conditions

The experiments were performed in a venlo-type greenhouse located at the experimental farm of Seoul National University (Suwon, Korea, Lat. 37.3° N, long. 127.0° E). Paprika (*Capsicum annuum* L. 'Fiesta') seedlings with 5-6 nodes were transplanted into 0.9 (L) x 0.15 (W) x 0.07 m (H) rockwool slabs (MaXXima, Cultilène, Tilburg, Netherlands). Ten days after transplanting into the rockwool cubes, the roots began to emerge at the bottom of the cube, at which time the slabs were placed in gutters with a plant density of 3 plants/m^2. There were two slabs for each system. To examine the transpiration amount and water supply, three irrigation monitoring and control systems and 18 total plants were used (Fig. Ⅱ-1). The experiments were carried out twice in summer and winter from Feb., 2011 through Mar., 2012. Paprika was sown and transplanted on Feb. 21 and Apr. 15, 2011, respectively, in summer and on Jul. 15 and Sep. 2, 2011, respectively, in winter.

Microclimate conditions, such as daytime and nighttime temperature, and relative humidity were automatically controlled by an environmental control system within the ranges of 25 - 30°C, 15 - 22°C, and 50 - 80%, respectively, during the experimental period. The electrical conductivity (EC) and pH of the nutrient solution were 2.6 - 3.0 $dS{\cdot}m^{-1}$ and 5.5 - 6.5, respectively. Every irrigation event was initiated when the cumulative radiation reached 100 $J{\cdot}m^{-2}$. The irrigation operating time was 06:00 - 18:30 and 06:30 - 18:00 in summer and winter, respectively. The plants were pruned to maintain two main stems, which were vertically trellised to a ‘V’ canopy system (Jovicich et al., 2004).

Measurements

Transpiration was measured by a precise irrigation monitor and control system that was developed by Protected Horticulture and Plant Factory Lab. at Seoul National University (Fig. Ⅱ-2). The amount of water uptake by each plant, water supply, and drainage were measured at 5 second intervals using load cells to calculate actual transpiration amount with following concept of Eq. Ⅰ-1.

Microclimates (radiation, temperature, and relative humidity), and root-zone environmental conditions (MC and EC of substrate) were also measured at the same intervals of weight measurement with suitable sensors to obtain the relationship between transpiration and environmental factors. The leaf area index (LAI) was calculated by measuring leaf length and width every week during the experimental period (Ta et al., 2012).

Transpiration Estimation Model

The transpiration rate was estimated with an equation (Eq. Ⅰ-2) that was modified from Penman-Monteith’s (P-M) equation (Ta et al., 2011b). Main concept of Eq. Ⅰ-2 was similar to P-M evapotranspiration equation. LAI and VPD were used as factors mainly affecting transpiration rate as in P-M equation. However, RAD in Eq. Ⅰ-2 was instant value (light intensity) not accumulated one as in P-M equation. And because the evaporation from surface of substrate was very small amount, it could be ignored. Using modified variables, the coefficients of Eq. Ⅰ-2 was refit to the experimental condition and paprika plant with non-linear regression function. For the coefficients of a, b, and k in this compensated transpiration equation, it used the following values: 9.55 e^{-4}, 0.03, and 0.84, with a range of LAI 0.63-3.52, respectively. Although VPD is one of the major factors that directly affects the estimation of transpiration rate in the above equation, it was assumed constant because air temperature and relative humidity were maintained within specified target ranges in our system.

Experimental methods

The relationship between transpiration rate and light intensity was investigated and compared using continuous transpiration data for 5 sunny days, 85 – 115 days after transplantation (DAT) (LAI = 3.0 - 3.5), in both summer and winter cultivations. The exact amounts of transpiration measured with the irrigation monitoring and control system was compared with the amount of transpiration estimated from Eq. Ⅱ-2. The transpiration rate was determined based on the weight changes of plants in a given unit time. In addition, at time intervals of 1, 10, and 60 min, the relationship between the measured transpiration amount and cumulative radiation was compared by considering the accuracy of sensor and plant response to water. The intervals of 1, 10, and 60 min were divided by 10, 5, and 1% average errors of observation against actual transpiration amounts, respectively. The transpiration rate per leaf area was estimated using the light intensity and LAI data from Eq. Ⅱ-2. Based on the results, the light intensity generally used for conventional irrigation was adjusted. The differences in accumulated radiation and water consumption in both summer and winter were compared between the modified and conventional irrigation methods.

Data Analysis

The data were analyzed with the statistical analysis program SAS 9.3 (SAS Institute Inc., UT, USA). The relationship between instantaneous radiation and transpiration rates were fit with a negative exponential curve. And coefficient values were derived by non-linear regression function. LSD test was used to compare the plant growth and productivity between control and treatment. Graphs were generated with SigmaPlot 13 (Systat software Inc., CA, USA).

RESULTS AND DISCUSSION

Instantaneous and Daily Accumulated Radiation Levels in Summer and Winter

The peak of light intensity inside the greenhouse was higher in the summer than in the winter at the experimental site (Suwon, Korea) (Figs. Ⅱ-3-A, B). Fluctuations in light intensity during the day were greater in summer (0-700 $W{\cdot}m^{-2}$) than in winter (0-400 $W{\cdot}m^{-2}$) (Figs. Ⅱ-3-A, B). Because light intensity may differ depending on the weather, region, latitude, and season, etc., it is difficult to find a relationship between the light intensity and the levels of radiation accumulated daily. Although the peak of light intensity during the day on Aug. 25, 2011 (Fig. Ⅱ-3-A) was nearly twice as high as that on Jan. 14, 2012 (Fig. Ⅱ-3-B), there was no significant difference in the accumulated radiation amount during the day, despite the fact there was a longer photoperiod in the summer.

The transpiration rate was utilized to determine the amount of irrigation required and was calculated based on the daily amount of radiation estimated with the compensated Penman-Monteith's equation. Even though the amount of radiation accumulated daily remains constant regardless of light intensity, the transpiration rate may differ with the fluctuations in light intensity that occur during the day (Ali et al., 2009). As the fluctuations in light intensity became larger, the transpiration rate was increasingly suppressed, especially under high light conditions. Fig. Ⅱ-4 showed an example of transpiration difference affected by fluctuation of light intensity. Although total daily accumulated radiation of both Aug. 24, 2011 and Jan. 14, 2012 was the similar to 459 $MJ{\cdot}m^{-2}$, but maximum light intensity were different as 692.4 and 459.2 W·m^{-2} on Aug. 24, 2011 and Jan. 14, 2012, respectively. And these differences in light intensity fluctuations caused daily accumulated transpiration (Fig. Ⅱ-4). Daily accumulated transpiration amount of at Aug. 24, 2011 was about 5% lower than that of at Jan. 14, 2012. Furthermore, the amount of fluctuations in the light intensity may be larger depending on the region (latitude) and climate conditions where the plants are growing (Ali et al., 2009; Rahimikhoob et al., 2012). Considering the obtained results, an accurate measurement of the light intensity is required for an accurate calculation of the radiation accumulation that reflects the transpiration rate (Rahimikhoob et al., 2012; Saez et al., 2012).

Estimated and Actual Transpiration Rates a Different Time Intervals

Transpiration rates were determined at intervals of 1, 10, and 60 min based on measurements of radiation accumulation and weight change obtained during the experimental periods in both summer and winter (Fig. Ⅱ-5-A). To estimate the transpiration rate, the compensated P-M equation was used to analyze the relationship between the transpiration rate and light intensity per cm^2 of leaf area. A linear relationship with a = 0.0637 and b = 1.7900 was determined (Fig. Ⅱ-5-A, Eq. Ⅱ-1).

$$Tr = a * RAD + b \qquad \text{(Eq. Ⅱ-1)}$$

where Tr and RAD mean transpiration amount (g) and radiation amount ($W \cdot m^{-2}$), respectively.

However, from the statistical analysis of the transpiration data, it was found that the relationship between light intensity and transpiration rate in a unit of leaf area were actually better represented with a nonlinear curve-fitting sigmoidal function (Eq. Ⅱ-2), which minimized the deviations between observed and expected y values in in the intervals examined (Fig. Ⅱ-5-A).

$$Tr = a / [1 + \exp(-(RAD - x_0) / b)] \qquad \text{(Eq. Ⅱ-2)}$$

where Tr and RAD mean the same in Eq Ⅱ-1. For the transpiration rates calculated at 1, 10, and 60 min, the values of x_0, a, and, b in the above equations and the R^2 values are listed in Table. Ⅱ-1. At an interval of 60 min for transpiration measurement to light intensity showed a similar trend to estimated transpiration rate with Eq. Ⅱ-2. However, estimated transpiration rates at a shorter interval were closer to the actual ones because the light intensity changing every seconds was reflected in the estimation. On the other hand, the error in the calculated transpiration rate was greater with a smaller R^2 value as the calculation intervals decreased (Table Ⅱ-1). Because transpiration response of plants to light intensity change was slower. At 1 min interval, F values were too small and the transpiration amount was 10% underestimated compare to actual one. A method of transpiration measurement with 10 min interval reduced the errors with satisfying the momentary transpiration concept.

At 10 min, the transpiration rate per unit leaf area increased proportionally to the light intensity at a range of 0-200 $W \cdot m^{-2}$ light intensity. But above 200 $W \cdot m^{-2}$, the transpiration rate did not significantly increase with increasing levels of light intensity. Because our data were largely collected in low light conditions below 250 $W \cdot m^{-2}$ (data not shown), the regression constants, R^2, in the transpiration equations were not so high in all three cases. The reason why the transpiration rates determined at periods of relatively high light intensities were lower than those obtained under low light intensity conditions is likely because the average light intensity values from the 10 min time point were used in this experiment. Furthermore, the use of shading screens for preventing the temperature from increasing too much during high light intensity periods may be a confounding factor. To overcome this situation, the data were collected as often as possible in the summer and winter seasons to reduce the amount of error.

Compensated Calculations of Accumulated Radiation Levels

The actual transpiration rates measured at 10 min are shown in Fig. Ⅱ-5-A. Eq. Ⅱ-3 was used to analyze the relationship between light intensity and the transpiration rate. Although the transpiration rate tended to increase as the light intensity increased, the transpiration rate measured at 10 min was proportional to light intensity until 200 $W \cdot m^{-2}$, while beyond this point the rate was almost constant (Fig. Ⅱ-5-A). With Eq. Ⅱ-2, the transpiration rate was estimated to be 27.27 $g \cdot m^{-2} \cdot 10min^{-1}$ at 400 $W \cdot m^{-2}$ light intensity, while the actual transpiration rate at this time was 14.96 $g \cdot m^{-2} \cdot 10min^{-1}$. This value at 400 $W \cdot m^{-2}$ corresponds to that at 207 $W \cdot m^{-2}$ (Fig. Ⅱ-5-B) Given that the actual transpiration rate was lower than the estimated one under high light conditions, the accumulated radiation used for irrigation control should be lower. From this estimated and actual transpiration rate data, a compensated equation that takes into account the light intensity and accumulated radiation to determine the irrigation methods was determined:

$$RAD' = a / [1 + \exp(-(RAD - x_0) / b)] - c \qquad \text{(Eq. Ⅱ-3)}$$

where RAD' and RAD mean calibrated radiation for accumulation ($W \cdot m^{-2}$) and actual radiation ($W \cdot m^{-2}$), respectively. The coefficients x_0, a, b, and c were 81.605, 1.410, 40.910 and 28.101, respectively. From these results, a calibrated light intensity like what was used in Fig. Ⅱ-6 should be applied to values of radiation accumulation when determining the amount of irrigation needed.

Unlike the estimated transpiration, the actual transpiration rate for a given light intensity could be measured by using a precise irrigation and control system (Ta et al., 2011; Ta et al., 2012). Eq. Ⅱ-3 is an important tool for exerting precise irrigation control in paprika cultivation. Because irrigation control is largely based on the levels of radiation accumulated in most paprika cultivation systems, an accurate measurement of transpiration rates at varying light intensities is a crucial factor. Therefore, an irrigation control method that accounts for varying light intensities would be useful for improving the efficiency of water use, which would allow cultivators to save water and nutrients, especially on large-scale commercial farms.

Comparison of the Estimated, Actual, and Calibrated Transpiration Rates

The actual transpiration rate was lower than the estimated one, and the differences were greater in the afternoon when the light intensity was relatively high (Fig. Ⅱ-7-A). However, the calibrated and actual transpiration rates were approximately the same in this experiment. The estimated, actual, and calibrated transpiration rates during the day were 0.814, 0.733, and 0.726 $kg \cdot plant^{-1} \cdot day^{-1}$, respectively (Fig. Ⅱ-7-B). The estimated transpiration rate was overestimated by approximately 10% compared to the actual and calibrated measurements. When irrigation is maintained at a drainage rate of 30% for optimum root-zone environments in paprika cultivation, the more than 10% of the supplied water can be saved when the calibrated light intensity is used to determine irrigation amounts.

The Relationship between Accumulated Radiation Levels and Water Usage Based on Calibrated Light Intensities

The actual accumulated radiation level differed from the compensated one depending on the light intensity distribution during the day in the summer and winter (Figs. Ⅱ-8-A, B). The actual accumulated radiation and the compensated levels determined by Eq. 5 were 512.8 and 475.4 $MJ \cdot m^{-2}$, respectively, on Aug. 22, 2011 (Fig. Ⅱ-8-A), and 450.2 and 438.1 $MJ \cdot m^{-2}$, respectively, on Jan. 14, 2012 (Fig. Ⅱ-8-B) in the summer and the winter, respectively. The longer the high light conditions lasted during the day, the greater the difference was between the actual and compensated cumulative radiation levels, especially in the summer. In the winter, the difference between the two values was not significant because of the relatively low light conditions compared to those in the summer. The accumulated radiation levels on DAT 85-114 were also compared in the same way as mentioned (Figs. Ⅱ-8-C, D). With calibrated light intensity, the accumulated radiation levels were approximately 1336 $MJ \cdot m^{-2}$, which is around 10% less than the levels measured without calibration in the summer (Fig. Ⅱ-8-C). However, this difference was not significant in the winter compared to that in summer (Fig. Ⅱ-8-D). The difference between actual and calculated radiation levels in the winter was approximately 557 $MJ \cdot m^{-2}$, which was approximately 5% of the levels measured without calibration. From these results, it was confirmed that the ratio between the effective radiation levels and transpiration during the day was higher in the winter than in the summer, and the error in the calculated levels of accumulated radiation during the experimental period (DAT 85 – 114) in the summer was more than twice that in the winter. When the external radiation is higher than 700 $W \cdot m^{-2}$ during the daytime in the summer, a significant difference in the accumulated radiation levels may not occur because of the shading screen that is placed in the greenhouse. Nevertheless, frequent exposure to relatively high light conditions occurs more often in the summer than in the winter. Thus, the difference between the measured and calculated cumulative radiation levels may be greater, as observed above.

Under similar daily radiation conditions, more water was supplied in the summer than in the winter (Figs. Ⅱ-9-A, B). On Aug. 22, 2011, 5 irrigation events were conducted when the irrigation was controlled by conventional methods (a water supply of 0.225 L per dripper for every 100 J of accumulated radiation), whereas water was supplied 4 times when the irrigation was controlled by a modified system (based on our equation to calculate radiation accumulation). Given that the transpiration rates of plants in both irrigation methods were similar, most of the extra water supplied by the conventional system was drained (Fig. Ⅱ-9-A). In contrast, in the winter (on Jan. 14, 2012), there was no difference between the amount of water supplied by the two irrigation methods (Fig. Ⅱ-9-B). During the experimental period (DAT 85-114), although there was no significant difference in duration of sunshine by 200 hours and 190 hours in summer and winter, but there were significant differences in the number of irrigations as 120 times and 102 times at conventional and modified irrigation method in summer, and 92 times and 91 times those in winter. Water was supplied 12 times more and one time more in the summer and winter, respectively, by the conventional irrigation method compared to the modified one (Figs. Ⅱ-9-C, D). From these data, it was determined that 4.05 L and 0.23 L of water per plant were saved in the summer and the winter, respectively, by using calibrated light intensity to determine the irrigation levels. The drainage amount was also reduced, as the water supply was decreased (Figs. Ⅱ-9-C, D).

Overall, it was observed larger differences in the amount of water supplied by the two irrigation systems in the summer than in the winter. Moreover, because of the saturate point of substrate moisture content of which used in experiment was 85%, and substrate moisture content maintained the range of between 69-85% during experimental period, it was confirmed that the differences in the amount of water supplied effected the drainage amount but not the transpiration rate. This is because excessive water was supplied to plants due to an overestimation of the light intensity in the summer. These results demonstrate that more water and nutrients were wasted with conventional irrigation management in summer cultivation. This problem occurred more frequently under high light conditions in the summer than in the winter, resulting in a less efficient use of water.

Comparison of Plant Growth with the Two Different Irrigation Methods

There were no significant differences in any measures of plant growth (plant height, number of nodes, leaf area, and number of fruit per plant) between the two irrigation methods at the end of the experiment in either the summer or the winter (Table. Ⅱ-2). Controlling the water supply based on the calibrated light intensity did not affect the plant growth. Because more water than was required by the plants was supplied with the conventional method, it is logical that a reduction in the irrigation amount did not affect the plant growth. This result indicates that by using the calibrated light intensity to determine the amount of irrigation, it can be expected to reduce the amount of water and nutrients wasted without affecting the fruit yield and quality of the paprika plants, especially in the summer.

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Table Ⅱ-1. The values for the coefficients in the transpiration equation used at intervals of 1, 10, and 60 min.

Measured interval (min)	x_0	a	b	R^2
	$Y = a / [1 + \exp(-(x - x_0) / b)]$			
1	118.173	8.133	55.228	0.69
10	81.605	14.968	40.910	0.82
60	232.303	33.219	79.298	0.83

Table Ⅱ-2. Plant growth (height, number of node, LAI) and reproduction (number of fruit) of paprika at the end of the experimental period in the summer and winter seasons. (Conventional: irrigation based on actual radiation, Modified: irrigation based on compensated radiation)

Treatment	Height (cm)	No. of nodes	LAI	No. of fruits
		Summer (Aug. 26, 2011)		
Conventional	160.8	28.3	3.37	8.8
Modified	162.1	28.1	3.24	9.1
Significance	ns	ns	ns	ns
		Winter (Jan. 20, 2012)		
Conventional	205.2	32.3	3.52	10.8
Modified	208.2	32.9	3.67	10.1
Significance	ns	ns	ns	ns

Fig. Ⅱ-1. A photograph of experimental view: 18 plants of paprika plants were grown for the experiment.

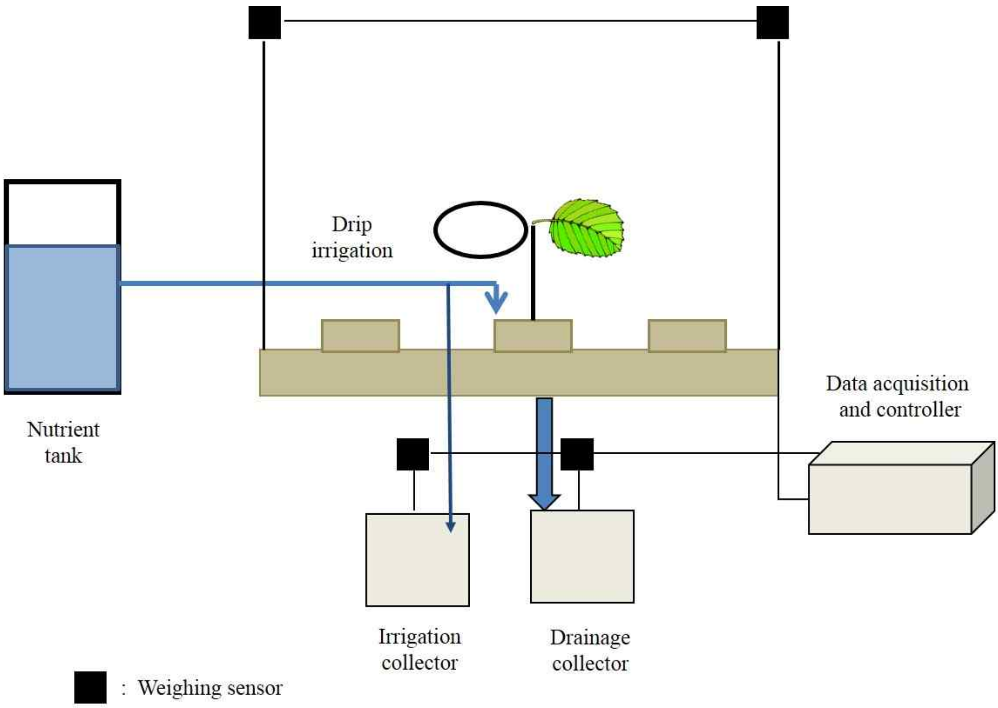

Fig. Ⅱ-2. A schematic diagram of the irrigation control system used in this experiment.

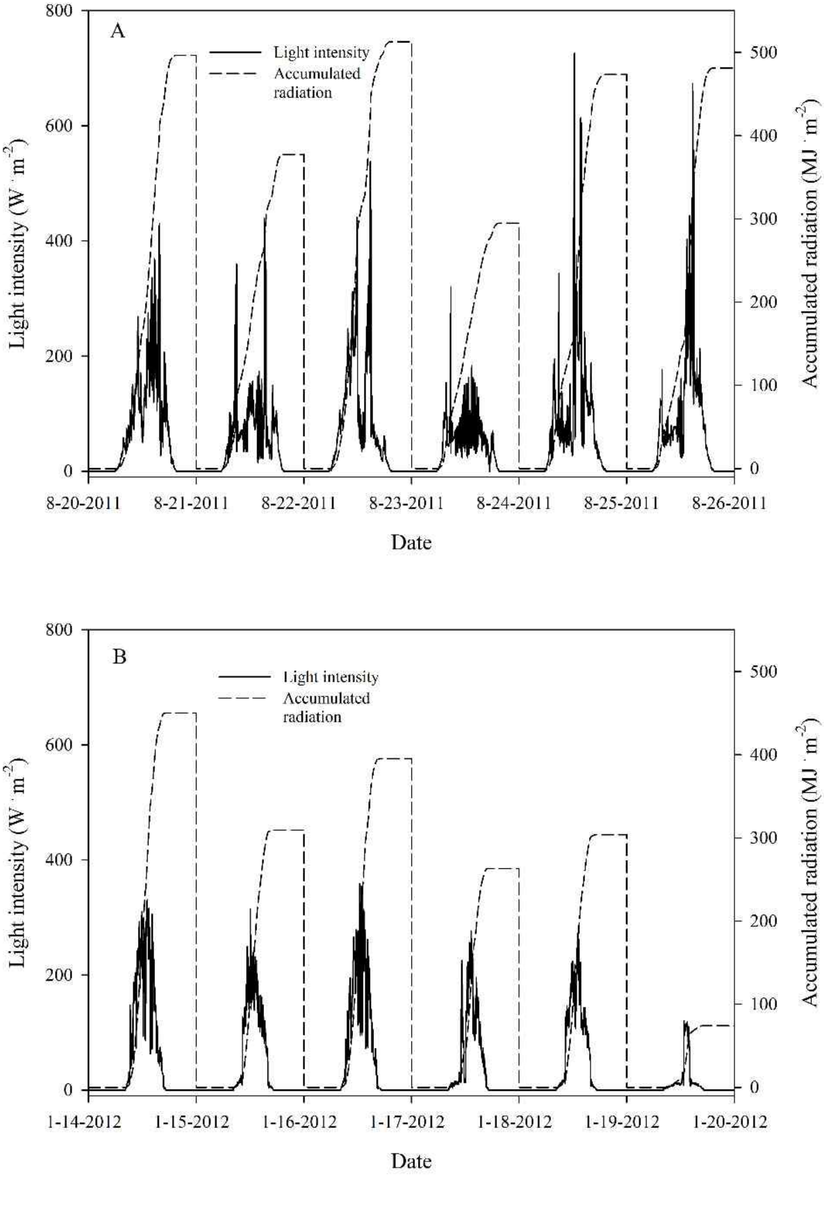

Fig. Ⅱ-3. Comparison of the light intensity and accumulated radiation for one day on sunny days in the summer (A) and winter (B) (Suwon, Korea).

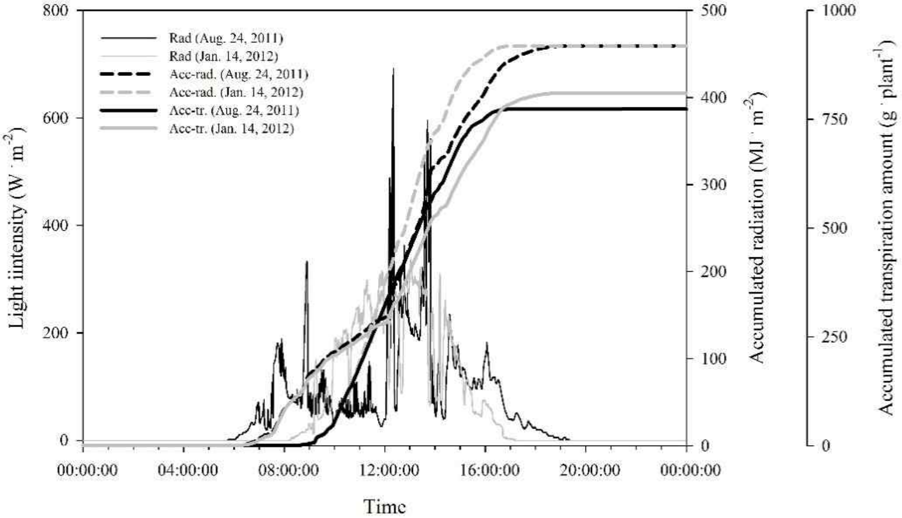

Fig. Ⅱ-4. Comparison of transpiration according to the different fluctuation in light intensity with same accumulated radiation. Rad, Acc-rad, and Acc-tr mean radiation, accumulated radiation, and accumulated transpiration, respectively.

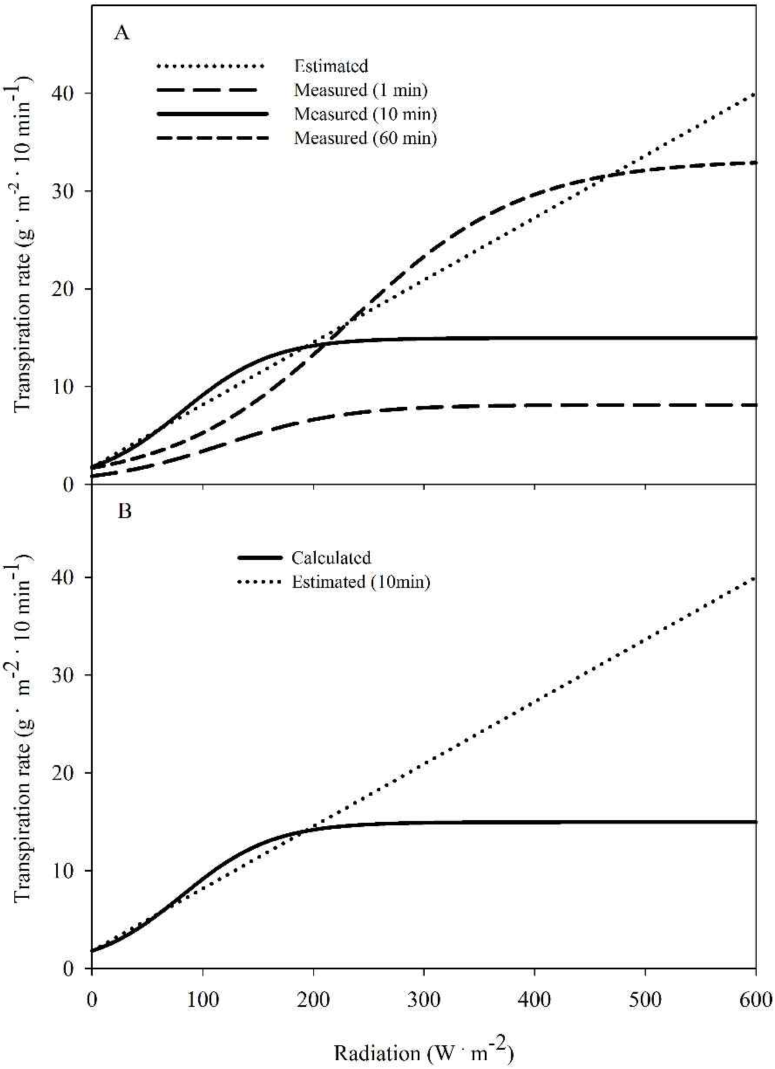

Fig. Ⅱ-5. A comparison of the estimated and measured transpiration rates (at 1, 10, and 60 min intervals) to light intensity per unit leaf area (A), and relationship between estimated and measured (10 min) transpiration amount at a certain radiation (B).

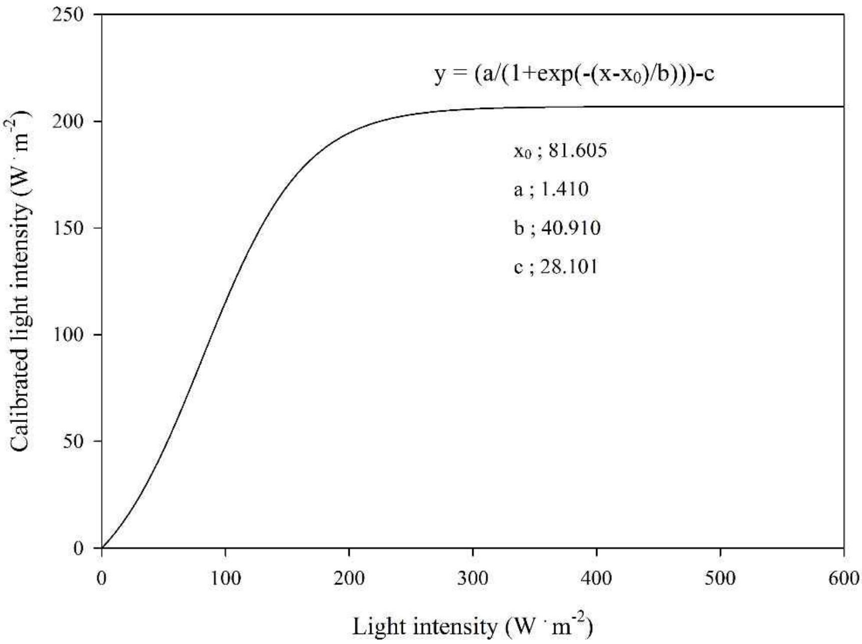

Fig. Ⅱ-6. The relationship between the actual and calibrated light intensities at 10 min intervals.

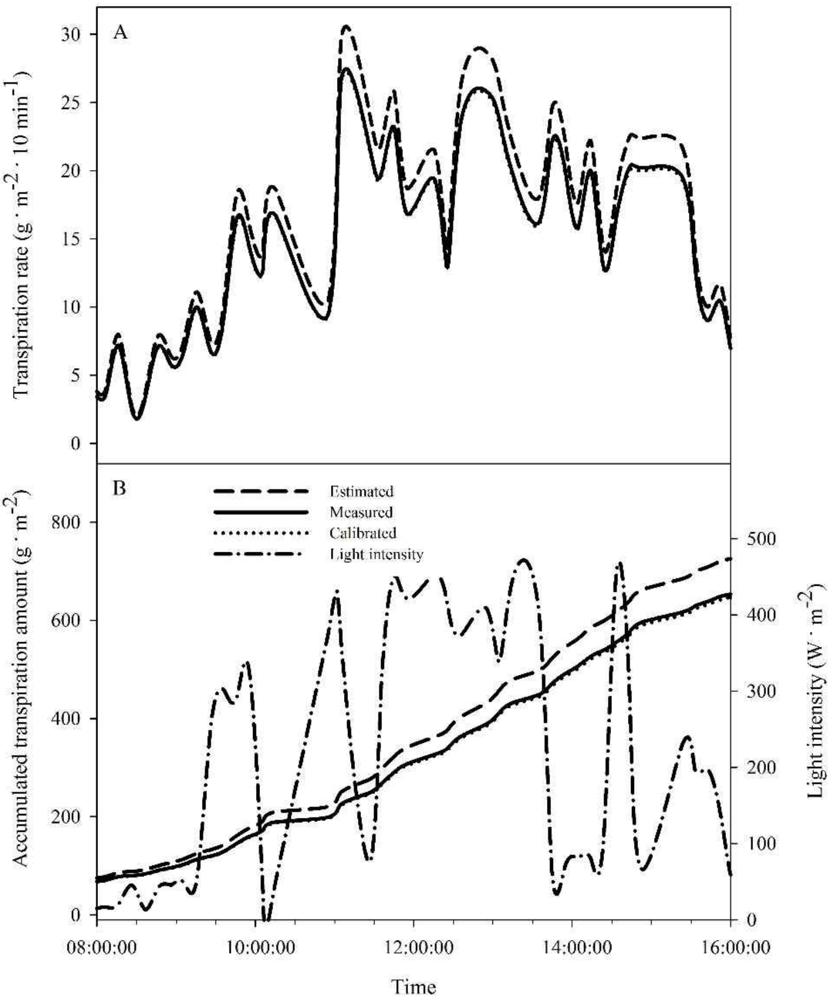

Fig. Ⅱ-7. Comparison of estimated, measured, and calibrated transpiration rates (A) and accumulated transpiration amounts per day by light intensity (B) (on Jun. 2, 2011 at LAI = 2.25).

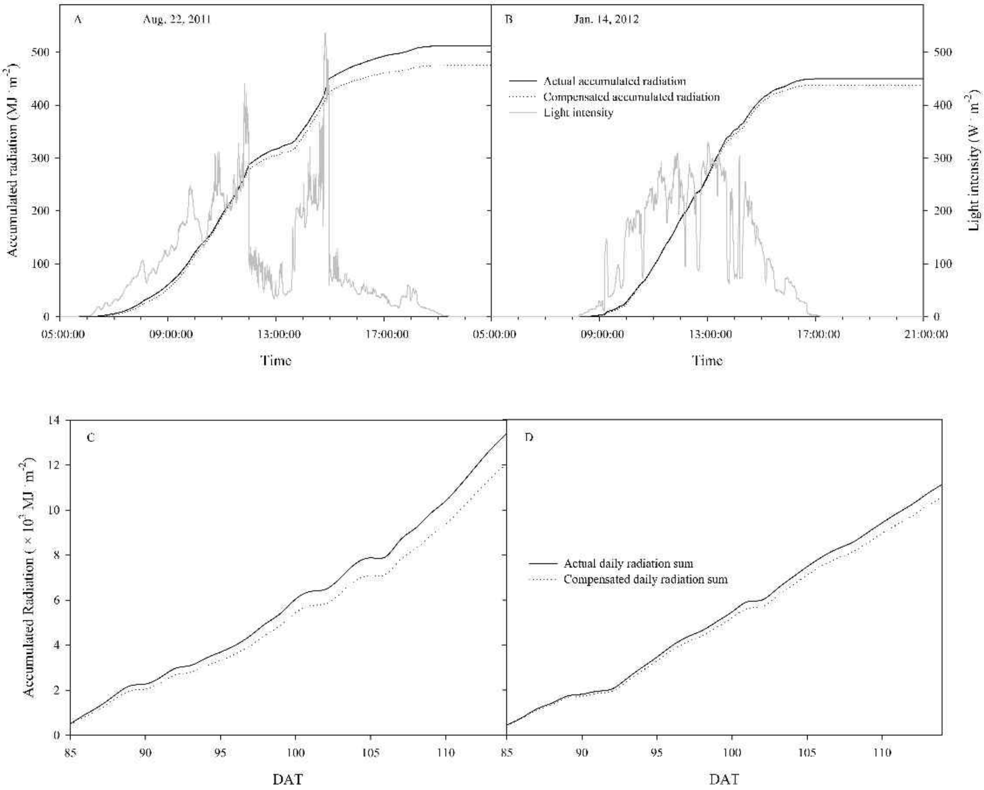

Fig. Ⅱ-8. Actual and compensated levels of accumulated radiation for one day (A = summer, B = winter), and actual and compensated cumulative radiation for one month (85-114 days after transplanting, DAT) (C = summer, D = winter).

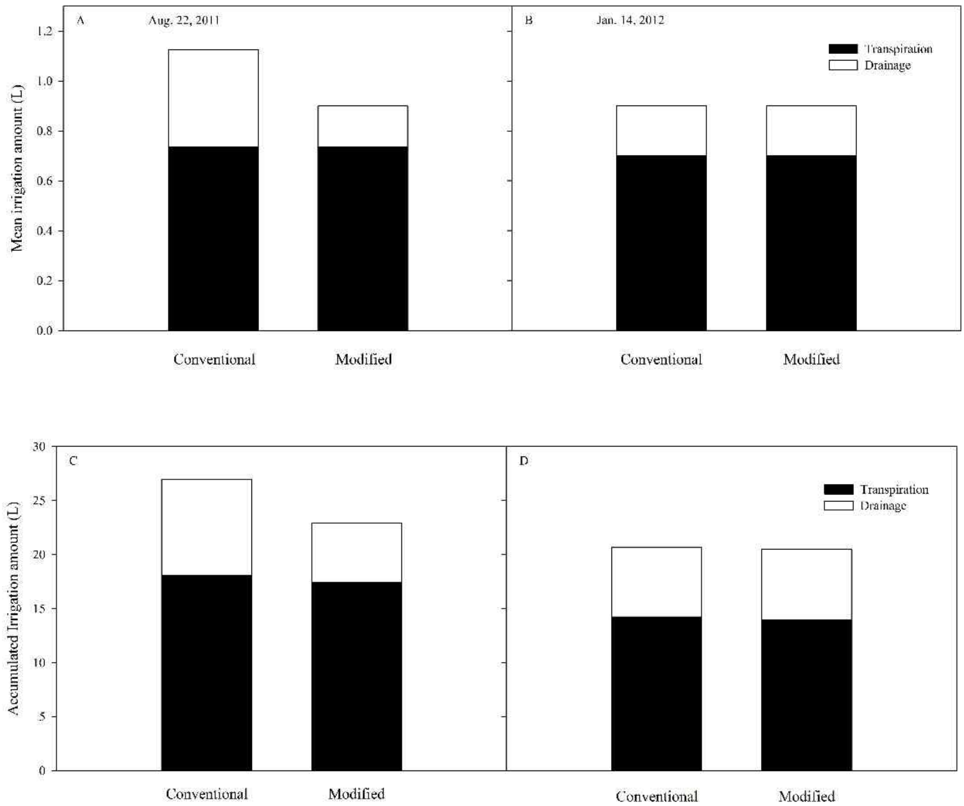

Fig. Ⅱ-9. Mean irrigation, drainage, and transpiration rate of paprika per plant for one day (A = summer, B = winter), cumulative irrigation, drainage, and transpiration rates for one month (85-114 days after transplanting) (C = summer, D = winter). Conventional and modified represent irrigation methods based on the actual and calibrated light intensities.

CHAPTER Ⅲ

Change in Substrate Electrical Conductivity by Moisture Content-Based Irrigation Control and its Subsequent Effect on Transpiration Rate, Water Use Efficiency, and Plant Growth in Soilless Culture of Paprika

ABSTRACT

Moisture content (MC) and electrical conductivity (EC) in substrate are major root-zone environment factors affecting transpiration rate and subsequent plant growth in soilless culture. For maintaining optimum root-zone environments, an efficient irrigation control considering substrate EC, MC, and transpiration are required. The objectives of this study were to clarify the relationship between substrate MC and EC, and to analyze the increase in substrate EC, plant growth, and water use efficiency under different moisture control regimes. Irrigation controls maintaining three regimes of substrate MC (70-85%, 60-85%, and 50-85%) were set as treatments and a conventional irrigation using accumulated radiation as a control. Subsequent changes in substrate EC and transpiration amounts at the different substrate MCs were continuously measured and their relationships were derived. Transpiration rate was more sensitive to substrate EC at general cultivation conditions of substrate EC 2.5-4.5 $dS \cdot m^{-1}$ and substrate MC 60-85%. It tended to decrease with increasing substrate EC and decreasing substrate MC. More water was consumed in a higher substrate MC controlled within in a narrow range of MC, however, substrate EC was well controlled below 4.5 dS·m^{-1} in substrate MC 70-85%. The relationship between the range of substrate MC and the increase in substrate EC was obtained with equations. Although the more water was supplied for 70-85% of substrate MC control, fruit productivity tended to increase than other 2 substrate MC (60-85% and 50-85%) control. It is expected that precise control of root-zone environments from the results can be used to increase fruit productivity and water use efficiency as well as to minimize plant water stress.

Additional keywords: irrigation control, substrate electrical conductivity, substrate moisture content, transpiration rate, water use efficiency

INTRODUCTION

Since transpiration is closely related to the promotion of crop growth and irrigation control, transpiration rate becomes an important indicator for plant growth diagnosis and irrigation strategy in soilless culture of paprika. In order to determine the transpiration for irrigation control, aerial environmental factors, such as accumulated radiation, and root-zone environmental factors, such as moisture content level in substrate have been considered. Particularly the relationship between aerial environmental factors and transpiration have been studied and irrigation methods proposed (Patane, 2011; Rao and Bhatt, 1988; Rogiers et al., 2011; Ta et al., 2011; Ta et al., 2012; Tai et al., 2010).

However, under the same aerial environmental condition, the transpiration rate can be affected by root-zone factors such as moisture content and EC level in substrate. Therefore, the relationship between root-zone environmental factors and transpiration should be clarified for more systematic irrigation strategy. Charbonneau et al. (1988), Dorais et al. (2001), and VanIeperen (1996) reported that the increase in substrate EC can act as drought stress to plants in soilless culture of tomato. In addition, Charbonneau et al. (1988) showed that osmotic water potential by substrate EC has great influence on plant water absorption especially in soilless culture system of protected horticulture than in soil culture system. Anothai et al. (2013), and Moreira and Cardoso (1998) studied on the effect of substrate moisture content and irrigation time interval on plant growth. The results indicated that water uptake by plants closely interacts with substrate moisture content with respect to irrigation interval. In addition, Havrda et al. (1989) and Nesmith et al. (1992) suggested that supplied nutrient EC should be adjusted considering the substrate MC in soilless culture because substrate EC generally increased with decreasing substrate MC. Similarly, Ta et al. (2012) suggested that frequent irrigation with a small amount could increase the transpiration with respect to the substrate MC and EC. In general, it is known that substrate MC related to matrix water potential directly affects the water uptake by root, and substrate EC which inverse proportional to substrate MC incidentally influence to plant transpiration as osmotic water potential.

Until now, most of researches have studied on general relationships between each root-zone environmental factor and plant response. However, for precise irrigation control, a systematic analysis of the relationship among root-zone environments such as substrate EC and MC, transpiration, and water use efficiency are required. The objectives of this study were to clarify the relationship between substrate MC and EC considering the transpiration, and to analyze the plant growth and water use efficiency under different root-zone environments such as substrate MC and EC.

MATERIALS AND METHODS

Experimental Condition

The experiment was conducted at the Experimental Farm of Seoul National University (Suwon, Korea, Lat. 37.3° N, long. 127.0° E). Paprika (*capsicum annuum* 'Fiesta') plants with 5-6 nodes were transplanted on rockwool slab [1.00 (L) x 0.12 (W) x 0.07 m (H) (Grotop, Grodan, Roermond, Netherlands)] at Jun. 1, 2013. Irrigation treatments were applied for 120 days from transplanting date to September 30, 2013. Transpiration amount and water supply were examined using a precise irrigation monitoring and control system which was developed by Shin et al. (2014) (Fig. Ⅰ-1) and 24 total plants were used. Planting density was three plants/m^2 and six plants in two rockwool slabs were used in each irrigation control system. Day and night temperatures, and relative humidity in the greenhouse were controlled at 25-30℃, 15-22℃, and 50-80%, respectively. The EC and pH of nutrient solutions were maintained at 2.4-2.8 $dS \cdot m^{-1}$ and 5.5-6.0, respectively. Nutrient solutions were not reused as open-type hydroponic systems. Nutrient solutions were supplied by a drip irrigation system, and flow rate of nutrient supply was 30 $cc \cdot min^{-1} \cdot dripper^{-1}$. The plants were pruned to maintain two main stems, which were vertically trellised to a 'V' canopy system (Jovicich et al., 2007) and the additional plant management of pruning and training were carried out every week.

Measurements

The measured data such as number of irrigation events, supplied water amounts, drainage amounts, drainage rate, substrate moisture content and EC, and transpiration were continuously collected by the irrigation control system. Transpiration amount and substrate MC were measured by calculating the weight changes in a unit time for reducing the error due to the sensitivity of the sensor [load cells (JSB-50 and JSB-20, CAS Co., Ltd., Yangju, Korea)]. The resolution of the load cells used in the experiment was 1g, and error range was less than 1% of measured value. Transpiration was measured at 10-min intervals. The average weight and water content of six fruit samples after harvest were measured. For the vegetative plant growth, plant height, the number of nodes and leaves, and leaf area index (LAI) calculated by measuring leaf length and width (Ta et al., 2012) data were collected every week.

Experimental Methods

Three irrigation methods based on substrate MC control were compared with a conventional irrigation method (control). Considering physical characteristics of the substrate, three ranges of substrate MCs were applied in the irrigation control as treatments: 70-85% (T1), 60-85% (T2), and 50-85% (T3). As a control, nutrient solutions of 110 mL was supplied to each plant whenever accumulated radiation reached at 100 $J \cdot m^{-2}$ (Table Ⅲ-1). The substrate MC 50% was set based on possible level of substrate re-saturation, and the substrate MC 85% was the value when gravitational water drained after irrigation. For accurate supply of nutrient solutions, a modified accumulated radiation (Shin et al., 2014) were used. Fig. Ⅲ-1 shows substrate MCs controlled well in each treatment according to set value. Irrigation time was set from sunrise to 18:00 in all the irrigation methods.

Data Analysis

The data were analyzed with the statistical analysis program SAS 9.3 (SAS Institute Inc., UT, USA). The relationship between root-zone environments and transpiration rates was analyzed with non-linear regression function. Exponential rise curve were basically used for curve fitting, and the result with the highest R^2 was selected. Transpiration amount were expressed as a form of data for unit leaf area considering plant growth stage and analyzed. Since transpiration rate did not affect significantly by substrate EC below 4.5 $dS \cdot m^{-1}$, the data in the range of 2.5-4.5 $dS \cdot m^{-1}$ were used for analyzing the relationship between substrate MC and transpiration amount. Four levels of substrate MCs 55%, 65%, 75%, and 85% were used for analyzing the relationship between substrate EC and transpiration amount. In both cases as above, the period with light intensity 250-400 $W \cdot m^{-2}$ were used for establishing the relationship according to the previous study (Shin et al. , 2014). Water use efficiency among treatments were compared with the data of supplied water amount and plant growth such as average fruit weight and moisture content, sugar content, fruit shape, number of fruits and nodes, plant height, and LAI. The data were analyzed by the method of mean separation by Duncan's multiple rage test at P=0.05. Graphs were generated with SigmaPlot 13 (Systat software Inc., CA, USA).

RESULTS AND DISCUSSION

Effect of Substrate MC and EC on Transpiration

With increase of substrate MC, the transpiration per unit leaf area showed a negative exponential rise in the range of substrate EC 2.5-4.5 dS·m^{-1} (Fig. Ⅲ-2-A). The relationship between substrate MC (%) and transpiration rate (y, g·600s^{-1}) was expressed as Eq. Ⅲ-1.

$$y = y_0 + a*[1-\exp(-b*MC)] \qquad \text{(Eq. Ⅲ-1)}$$

where the coefficients y_0, a, and b were -93.381, 93.385, and 0.209, respectively. The transpiration rates were 0.00380, 0.00376, 0.00347, and 0.00111 g·s^{-1}·cm^{-2} at substrate ECs 80%, 70%, 60%, and 50%, respectively. At the substrate MC 50%, transpiration rate was drastically decreased to a 70.8% level of the maximum transpiration rate occurred at substrate MC 80%. From the results, it was considered that the transpiration rate was not significantly affected by substrate MC in the range of 60-85%, which were recommended for paprika cultivation (Hellemans, 2006). In this experiment, it was considered that the wide range of substrate EC 2.5-4.5 dS·m^{-1} at the same substrate MC condition caused the increment in the standard error with a lower regression constant (R^2=0.62) because relatively small number of data below substrate MC 50%. Although confidence level of regression curve could be relatively lower at the low substrate MC condition, the overall trend could be figured out with the above results.

On the other hand, substrate EC gave a more sensitive effect on transpiration rate than substrate MC (Fig. Ⅲ-2-B). However, the regression constants at the relationship between substrate EC and transpiration rate in the range of substrate MC 55-85% were not high like at that between substrate MC and transpiration rate. Gaussian curve was selected for describing the relationship between transpiration rate (y, $g \cdot 600s^{-1}$) and substrate EC ($dS \cdot m^{-1}$) (Eq. Ⅲ-2).

$$y = a*\exp[-0.5\{(EC-x_0)/b\}^2] \qquad \text{(Eq. Ⅲ-2)}$$

where the coefficients x_0, a, and b are listed in Table Ⅲ-2. At substrate MCs 65%, 75%, and 85%, reduction of transpiration rate with increase of substrate EC was smaller, whereas it was relatively larger at the substrate MC 55%. For instance, at substrate EC 8.0 $dS \cdot m^{-1}$, transpiration rates at substrate MCs 55%, 65%, 75%, and 85% could be 38.5%, 33.8%, 33.7%, and 31.4%, respectively, lower than the maximum transpiration rate. Substrate EC was more sensitive to transpiration rate response at relatively high substrate MC. Fig. Ⅲ-2 showed that transpiration rate was sensitively responding to substrate EC than substrate MC in the range of substrate MC 60-85% and substrate EC 2.5-6.5 $dS \cdot m^{-1}$, which are general growing conditions of paprika cultivation.

Although VanIperen (1996) and Xu et al. (1993) indicated that both substrate MC and substrate EC can act as limiting factors in water absorption by plants, the effect of substrate MC on transpiration rate was not significant in the range of substrate MC 60-85% in this experiment. On the other hand, similar to previous researches, transpiration rate was great influenced by substrate EC (Charbonneau et al., 1988; Dorais et al., 2001; VanIeperen, 1996). It could be considered that osmotic water potential by the difference in nutrient concentrations around roots act as a larger limiting factor than matrix potential by physical properties of substrate in water uptake from plant roots in soilless paprika cultivation.

Effect of MC on Substrate EC Increase

The maximum substrate EC in a day tended to increase with progress of plant growth in all the treatments and control (Fig. Ⅲ-3-A). Among the treatments, substrate EC significantly increased in the control. Substrate EC increased to 8.0 $dS \cdot m^{-1}$ during experimental period in the control where any management reducing substrate EC were not applied. Substrate ECs increased and tended to be stabilized at 4.5 $dS \cdot m^{-1}$ both in T1 and T2 treatments where the minimum MCs were controlled at 70% and 60%, respectively. According to Fig. Ⅲ-2-B, it could be a range that does not give a significant effect on transpiration rate. The lower the controlled minimum substrate MC was, the higher the substrate EC became (Fig. Ⅲ-3-A).

The relationship between the increase in substrate EC (y, $dS \cdot m^{-1}$) and the range of substrate MC fluctuation with growth stage (DAT, described as days after transplanting) showed an exponential curve as in Eq. Ⅲ-3 (Fig. Ⅲ-3-B).

$$y = y_0 + a * \exp(b * MC) \quad \text{(Eq. Ⅲ-3)}$$

where the coefficients y_0, a, and b are listed in Table Ⅲ-3. Regardless of growth stage, increase in substrate EC did not occur until 25% of substrate MC change (= substrate MC 65%), but rapidly increased beyond that during experimental period. The larger the substrate MC change contributed significantly to the increase in substrate EC (y, $dS \cdot m^{-1}$) as growth proceeded to late stage.

From the results, the relationship between the increase in substrate EC and substrate MC change with growth stage (DAT) could be shown as in Eq. Ⅲ-4.

$$y = a+b*\exp(c*DAT)+d*\exp\{-0.5*(e+f*DAT\}^2)+\{g+h*DAT+(i*DAT^2)\}*MC \quad \text{(Eq. Ⅲ-4)}$$

where the coefficients a, b, c, d, e, f, g, h, and i were 2.065, -2.518, -0.016, $1.804*10^{-3}$, -2.875, 0.033, 0.315, 0.003, and $1.567*10^{-5}$, respectively. In general irrigation strategies, the drainage rate is maintained at more than 30% for accumulated salts in substrate to be leached for substrate EC control (Hellemans, 2006). However, depending on the result of this experiment, it was found that control the range of substrate MC could be more effective to the control of substrate EC with 25% below from the saturated substrate MC which was 85% in this experiment.

Considering that root-zone environments such as substrate EC affect water absorption by plant roots (Havrda et al., 1989; Nesmith et al., 1992), it was presumed that the increase in substrate EC as shown in the control was due to the salt accumulation in substrate by limited water supply (Podesta et al., 2010). Although intended water stress was applied for switching vegetative growth to reproductive growth in Solanaceae crops, unintended water stress by other environmental factors might cause a physiological disorder. There was no significant difference in occurrence of physical disorders among treatments in this experiment because paprika ‘Fiesta’ cultivar was relatively unsusceptible to substrate EC change. However, as reported by Dorais et al. (2001), limitation of water absorption in plant roots by increasing substrate EC can cause a physiological disorder such blossom-end rot and reduce the fruit production in tomato cultivation.

Effect of Substrate MCs on Water Consumption and Water Use Efficiency

In T1 and T2 treatments the more water was supplied than in the control during experimental period and the increases in transpiration amount showed similar trends to those of supplied water amount (Fig. Ⅲ-4-A). Supplied water amounts in T1 and T2 were up to 7.8% and 3.6%, and the transpiration amounts were 10.7% and 2.3% higher than those in the control, respectively. In contrast, both supplied water and transpiration amounts in T3 were respectively 1.6% and 4.4% lower than those in the control. Transpiration efficiency (total transpiration amount / total irrigation amount) in T1 was 72%, only 2% higher than that in the control, while it was similar in T2 and 2% lower in T3. Particularly the low transpiration amount and transpiration efficiency in T3 could be explained by the limitation of transpiration.

Based on the water consumption and transpiration efficiency, it was considered that the conventional irrigation method restricts the transpiration amount against the maximum potential as similarly shown in T2. As shown in Fig. Ⅲ-1, the fluctuation of substrate MC became greater at the longer irrigation interval and caused the increase in substrate EC, resulting in restriction of transpiration. This result means that the irrigation interval based on accumulated radiation in conventional irrigation method was relatively long. VanIeperen (1996) reported that the increased osmotic potential of root-zone could restrict the water uptake by plant roots. Therefore, reducing the substrate MC change by frequent irrigation can improve the transpiration efficiency. Although the increasing trend of substrate EC in T1 was similar to that in T2, the transpiration efficiency in T1 was higher because better conditions for transpiration was provided in T1 by more frequent irrigation than in T2. Ta et al. (2012) reported the similar results on analysis of transpiration efficiency at different irrigation intervals.

As the irrigation interval became shorter by treatment, the number of irrigation events during the day increased with decrease of irrigation amount at each irrigation event (Fig. Ⅲ-4-B). Particularly clear differences were shown between T1 and the control: average number of irrigation events was 5 in the control and 9 in T1. On the other hand, supplied water amount at each irrigation event in T1 was 60% of that in the control. There were no differences in irrigation and transpiration amounts between T3 and the control.

Effect of Substrate MCs on Plant Growth and Plant Productivity

In vegetative growth, there were no significant differences in number of nodes, plant height, and leaf area index (LAI) among the treatments. However overall plant growth in T3 and the control were not good compared to those in T1 and T2 due to the insufficient water supply by the same reason as discussed in Fig. Ⅲ-3-A. The frequent change in substrate EC is considered to cause a drought stress for plant growth. It was reported that new leaves unfolding delayed and plant height became shorter due to insufficient water supply (Bernstein et al., 2010; Podesta et al., 2010; Rao and Bhatt, 1988; Sommer et al., 1999; Wang et al., 1997)

In reproductive growth, there showed a significant difference only in number of fruits among the treatments. Average 7.0 fruits per plant were produced in T1 during 120 days of experimental period, while average 5.6 fruits per plant were produced in the control (Table Ⅲ-4). The worst results in fruit production in the control could be attributed to the insufficient water supply like mentioned above in vegetative growth. It was assumed that due to insufficient water supply the more fruit and flower drop occurred in the control and T3 treatment, followed by the decrease in fruit production (Barta and Tibbitts, 2000; Li et al., 2009; Moreshet et al., 1999). Although appropriate stress to plants gives a positive effect on fruit quality such as secondary metabolites and sugar content, the increase in these contents has an inverse relationship with plant productivity (Azhar et al., 2011; Stuhlfauth et al., 1987). Considering no significant difference in sugar content of fruit in this experiment, the water stress beyond substrate MC 50% did not seem to affect the sugar content of fruits.

The analogous trends appeared in comparison with fruit quality and plant growth with no significant differences. Fruit water use efficiency (irrigation amount for fruit production) was higher in all treatment than in the control (Fig. Ⅲ-5). Fruit water use efficiency of T2 treatment was similar to that in T1 and it showed different result of fruit production. Although the number of produced fruit in T1 showed a tendency to be larger than in T2, fruit water use efficiency assumed to be similar because there were little effects on transpiration amount by the increase in substrate EC.

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Table Ⅲ-1. Treatments of the experiment.

	Control	Treatment		
		T1	T2	T3
Irrigation method	Irrigation start at 100 J·cm^{-2} of accumulated radiation with 100 mL/plant/event	Substrate moisture content		
		70 - 85%	60 - 85%	50 - 85%

Irrigation was operated from sunrise to 18:00.

Table Ⅲ-2. Coefficient values and regression constants of Gaussian curve which represents the relationship between substrate electrical conductivity (y, EC) and transpiration rate with substrate moisture content (x, MC).

Substrate MC (%)	$y = a \cdot \exp(-0.5((x-x_0)/b)^2)$			
	a	b	X_0	R^2
85	0.0037	7.152	2.119	0.42
75	0.0032	6.118	2.236	0.53
65	0.0025	5.528	2.818	0.51
55	0.0019	5.124	2.922	0.38

Table Ⅲ-3. Coefficient values and regression constants of exponential curve which represents the relationship between the increase in substrate EC (y) and the fluctuation range of substrate moisture content (x) with growth stage (DAT, days after transplanting).

Growth stage (DAT)	$y = y_0 + a \cdot \exp(b \cdot x)$		
	y_0	a	b
20	0.257	1.703×10^{-5}	0.272
40	0.665	4.187×10^{-4}	0.224
60	1.094	1.301×10^{-3}	0.208
80	1.403	1.776×10^{-3}	0.202
100	1.572	1.520×10^{-3}	0.205
120	1.649	1.195×10^{-3}	0.212

Table Ⅲ-4. Plant growth and yield as affected by substrate moisture content (MC).

Treatment	Reproductive growth					Vegetative growth		
	Fruit weight (g)	Fruit moisture content (%)	Sugar content (Brix)	Fruit shape (width/height)	No. of fruits	No. of nodes	Plant height (cm)	Leaf area index ($m^2 \cdot m^2$)
Control[z]	202.0 ± 15.21[y]	75.3 ± 5.76	8.6	0.7	5.6 ± 0.73 bc	22 ± 1	148.3 ± 12.2	3.0 ± 0.3
T1	215.7 ± 21.43	81.2 ± 2.34	8.3	0.8	7.0 ± 0.74 a	24 ± 2	168.9 ± 8.8	3.5 ± 0.2
T2	222.6 ± 18.93	79.8 ± 4.82	8.4	0.7	6.3 ± 0.58 ab	23 ± 2	161.6 ± 11.3	3.4 ± 0.3
T3	207.8 ± 17.67	76.3 ± 2.93	8.4	0.7	5.7 ± 0.62 bc	22 ± 1	153.7 ± 9.1	3.2 ± 0.3
Significance	NS	NS	NS	NS	*	NS	NS	NS

[z]See Table Ⅲ-1.
[y]mean ± SE (6 replications).
NS,* Nonsignificant or significantly different at P=0.05, respectively.

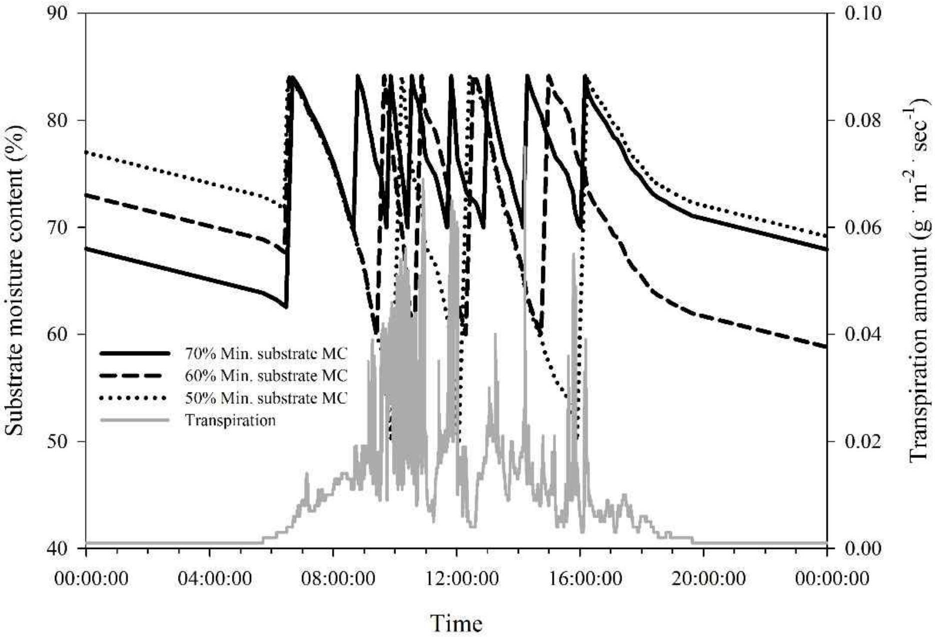

Fig. Ⅲ-1. Controlled situation of substrate moisture contents in T1, T2, and T3 with transpiration rate on Jul. 20, 2013. See Table Ⅲ-1 for T1, T2, and T3.

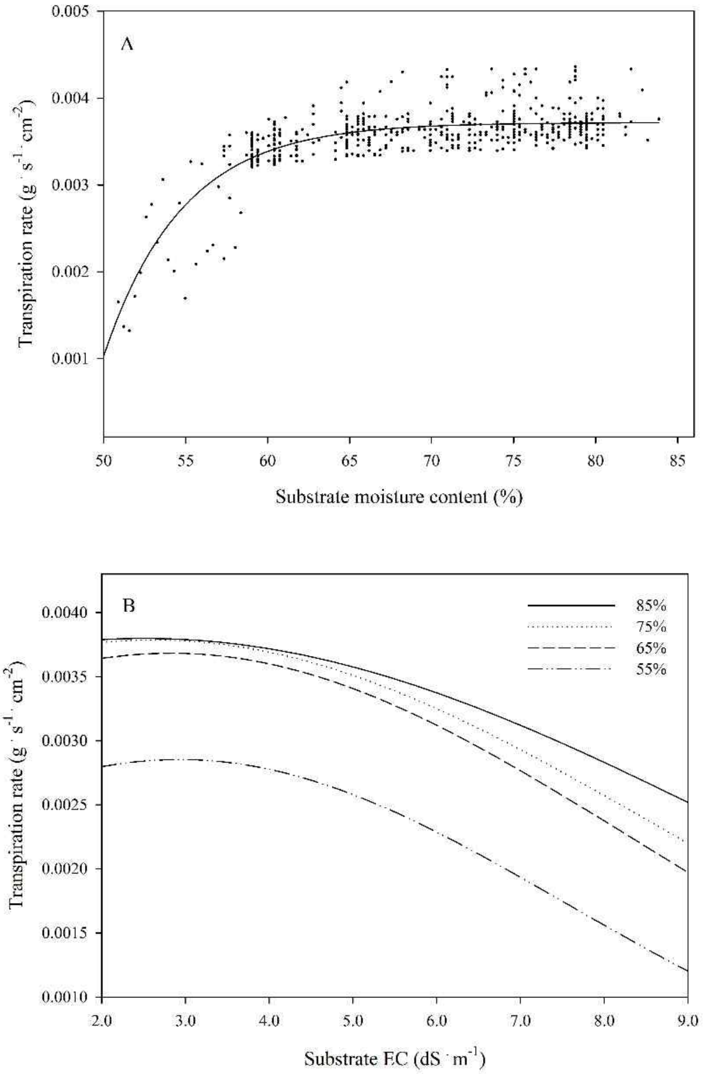

Fig. Ⅲ-2. Relationships between substrate moisture content (MC) and transpiration rate in the range of substrate EC 2.5-4.5 $dS \cdot m^{-1}$ (A) and between substrate EC and transpiration rate at different substrate moisture contents (MC, B).

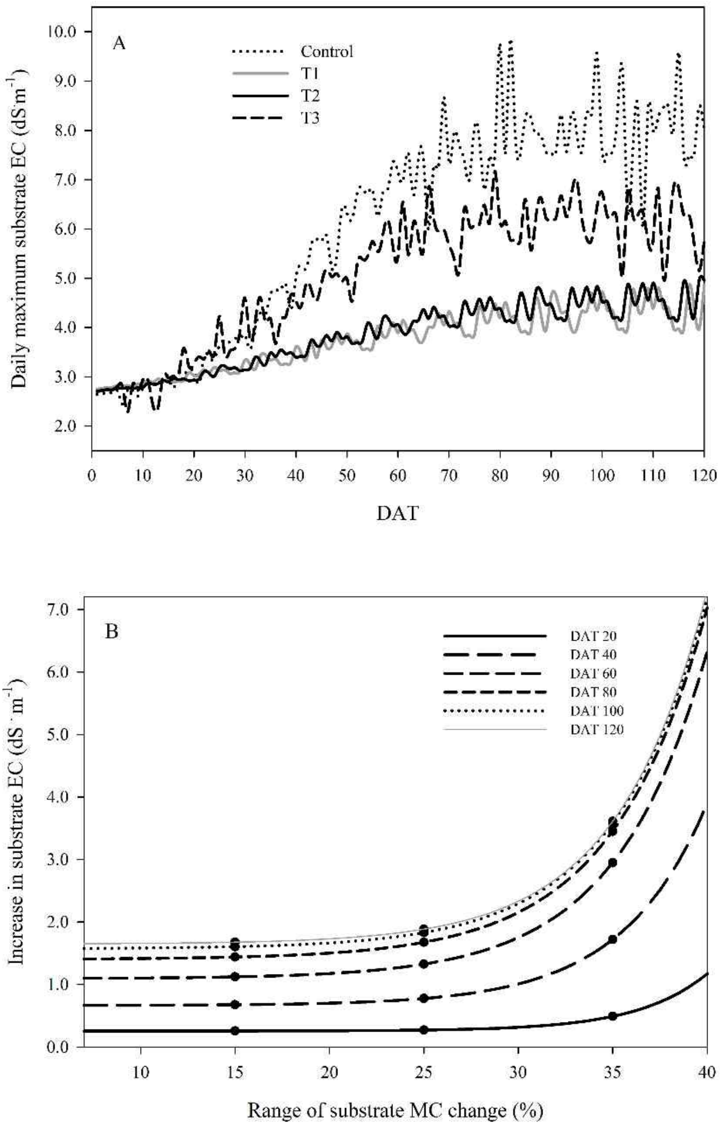

Fig. Ⅲ-3. Daily maximum substrate ECs as associated by different irrigation treatments (A) and the increases in substrate EC at different growth stages (DAT, B) among different substrate moisture contents (MC). DAT means days after transplanting. See Table Ⅲ-1 for Control, T1, T2, and T3.

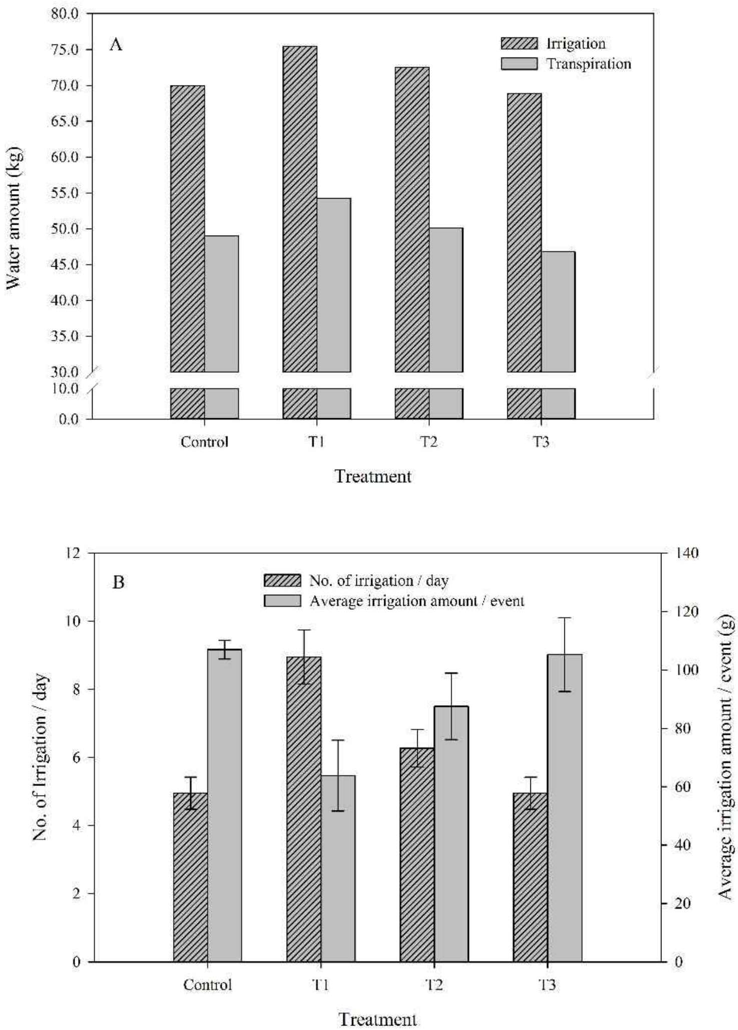

Fig. Ⅲ-4. Accumulated irrigation (Ir) and transpiration (Tr) amounts of paprika plants (A) and number of irrigation for a day and average irrigation amount per event (B) among different substrate moisture contents (MC). See Table Ⅲ-1 for Control, T1, T2, and T3.

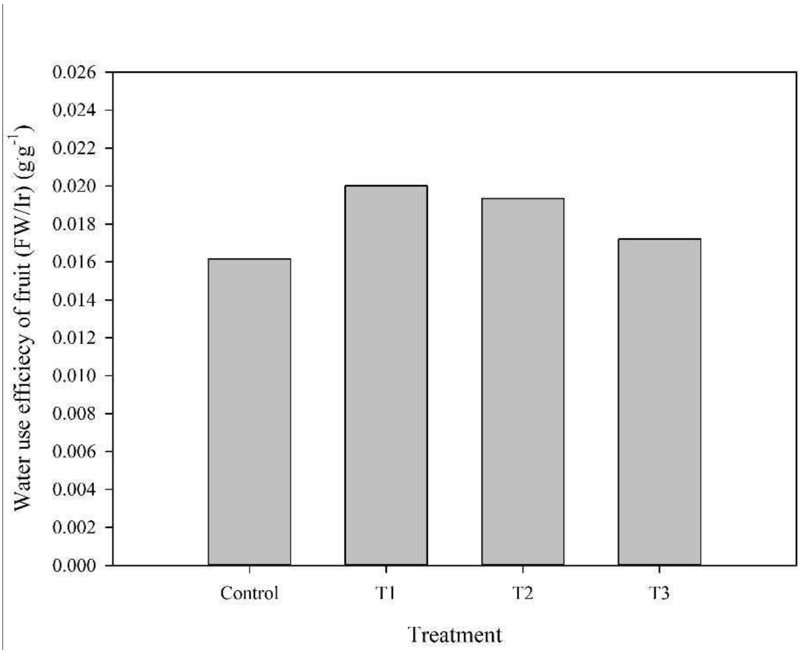

Fig. Ⅲ-5. Water use efficiency of fruit among different substrate moisture contents (MC). See Table Ⅲ-1 for Control, T1, T2, and T3.

CHAPTER Ⅳ

Evaluation of a Modified Irrigation Method Using Compensated Value of Accumulated Radiation and Precise Controls of Substrate Moisture Content and Electrical Conductivity in Soilless Culture of Paprika

ABSTRACT

Since irrigation strategy has a direct influence on productivity and production cost in soilless culture of paprika, more efficient irrigation methods are required. The objective of this study was to compare water use efficiency and crop productivity between a conventional irrigation method (CIM) and a modified irrigation method using a developed precise irrigation control system (MIM). Accumulated radiation was used as an irrigation index in CIM as control, while compensated value of accumulated radiation as well as precise controls of substrate moisture content (MC) and electrical conductivity (EC) were used for irrigation control in MIM. Plant growth and water use efficiency were compared between both irrigation systems. The experiment was carried out in a commercial farm cultivating paprika in Hwasung, Korea. In MIM, substrate MC was well controlled in the range of 69-85%, and showed a narrow fluctuation compared to the control. And substrate EC was maintained within 2.4-4.6 $dS \cdot m^{-1}$ in MIM during experimental period, while increased up to 7.9 $dS \cdot m^{-1}$ in the control. Water consumption and water use efficiency of fruits were 9.9% and 3.7% higher in MIM than in CIM. Overall plant growth was

better in MIM than in CIM. From the results, it could be concluded that the modified irrigation method (MIM) improved the productivity of paprika in soilless culture.

Additional keywords: fruit productivity, production cost, system performance, water saving

INTRODUCTION

Since paprika plants show a high sensitivity to irrigation control among Solanaceae crops (Sezen et al., 2006), an optimal irrigation strategy should be required to increase fruit production as well as to save production cost (De Pascale et al., 2011; Karam et al., 2009), especially in large-scale environmental controlled greenhouses. In fact, water management is one of the important works for paprika cultivation, but it is difficult to control efficiently due to various environmental conditions and their changes according to region. Until now, most of irrigations have been managed by grower’s experience and conventional cultivation manuals. To maintain optimal water conditions in substrate, development of systematic irrigation systems with real-time irrigation control responding to plant water status is required.

Many researches of algorithms for irrigation control have been focused on active water management considering crop conditions to solve a problem of conventional irrigation method. There were several attempts to apply water transport properties according to substrate type and irrigation method for irrigation management (Bougoul and Boulard, 2006; Kong et al., 2012). Liu et al. (2012) and Zotarelli et al. (2011) studied the irrigation criteria with moisture content measurement using moisture sensors. In addition, Bryla et al. (2010) calculated the amount of water that should be supplied by measuring plant and substrate weight. Bonachela et al. (2006) developed an irrigation strategy using accumulated weather data. However, crop response to water uptake was not quantified through these researches of irrigation methods. Shin et al. (2014b) quantified transpiration amount for monitoring the crop response to water uptake, and it was used as an indicator for irrigation control. And Shin et al. (2014b) also showed that transpiration rate did not proportionally increase with increase of light intensity especially in high-light condition, and suggested a compensated equation of the accumulated radiation conventionally used in irrigation control. In addition, as limited root-zone conditions may act as drought stress of paprika (Ben-Gal et al., 2008; Kurunc et al., 2011; Morales-Garcia et al., 2011), the importance of root-zone control and appropriate range of root-zone conditions were proposed.

For improving fruit production and saving production cost, systematic irrigation strategies making adequate root-zone conditions in commercial farms are required. Therefore a precise irrigation system considering plant water responses to aerial environmental factors as well as root-zone conditions are needed. The objectives of this study were to verify the performance of a modified irrigation method using precise irrigation control system (MIM) in a large-scale commercial farm and to compare the plant growth and water usage between MIM and a conventional irrigation method (CIM).

MATERIALS AND METHODS

Experimental Conditions

The experiment was conducted in a venlo-type greenhouse at the commercial farm of ‘Hwasung 21’ (Hwasung, Korea, Lat. 37.0° N, long. 126.8° E) (Fig. Ⅳ-1). Paprika (*capsicum annuum* ‘Veyron’) was transplanted on rockwool slab [(1.20 (L) x 0.12 (W) x 0.07 m (H) (Grotop, Grodan, Roermond, Netherlands)] at June 8, 2012. Irrigation was applied at 85 days after sowing (DAS) were arranged in two rows, for each lane, and 90 plants in each row were planted with spacing of 3.6 plants·m^2. Total 360 plants (180 plants for each treatment) were used for the experiment. The range of nutrient EC and pH which was supplied during the experimental period were 2.4 - 2.8 dS·m^{-1} and 5.5 - 6.0, respectively. Nutrient EC and pH were equally maintained both of in the control and irrigation treatment. Nutrient solution was not reused after irrigation. Temperature and relative humidity inside the greenhouse were controlled with the range of 15-29℃ and 50-80%, respectively during experimental period. Plants were pruned in the form with 3 main stems. Axillary shoots of flower and leaf were pruned according to management manual [two fruits every 2 nodes (Hellemans, 2006)]

Measurements

Number of irrigation events, supplied water amounts, drainage amounts, drainage rate, substrate MC and EC, and transpiration were continuously collected using the irrigation monitoring and control system developed by Shin et al., (2014b). Microclimates of radiation, temperature, and relative humidity were measured every 5 sec. Leaf area index (LAI) was calculated by measuring leaf length and width every week during the experimental period (Ta et al., 2012). Supplied water amount and water use efficiency were compared. Transpiration amount was obtained by calculating the weight change in the substrate with plant measured every 10 min by sensors [load cells (JSB-50 and JSB-20, CAS Co., Ltd., Yangju, Korea)]. Since daily weight increase in the plant was less than 1% compared to the total weight change in the substrate with plant during the day, substrate MC was calculated from irrigation and drainage amounts, and the total weight change. The resolution of load cells was 1g, and error range was less than 1% of measured value. Plant height, number of nodes, leaves, and fruits were measured every week for comparing the plant growth. From the collected data, water use efficiency for plants growth were calculated and compared. Sugar contents of three fruits at each treatment were measured after harvest for comparing fruit quality (RHB-32, Will Science Co., Ltd., Seoul, Korea).

Control of Irrigation Interval and Amounts

In order to verify the performance of MIM compared to CIM, irrigation interval and amount were controlled as described in Table Ⅳ-1. The water amount 110 mL were supplied to each plant every 100 $J{\cdot}m^{-2}$ of radiation accumulation in CIM and every 100 $J{\cdot}m^{-2}$ of compensated radiation accumulation in MIM. Compensated value of accumulated radiation (RAD’) was calculated from the accumulated radiation (RAD) generally used in CIM and applied to MIM (Eq. Ⅱ-3), because transpiration does not increase in proportion to light intensity, especially in the region of high light intensity (Shin et al., 2014b)..

The same irrigation operating time from sunrise to 15:30 in CIM was applied to MIM. Following the previous research (Shin et al., 2014a), the criteria of substrate MC (below 70%, 15% from the maximum moisture content) and EC (above 4.5 $dS \cdot m^{-1}$) were added to cumulative radiation as a factor which determines the irrigation start in MIM. Once irrigation started, it stopped when substrate MC reached 85% or substrate EC decreased below 2.5 $dS \cdot m^{-1}$ in MIM. Since the variation in substrate EC was not large under controlled substrate MC, control of substrate EC was used as adjunctive function for stability of root-zone conditions in MIM. The control performance of two functions was compared with the results of control.

RESULTS AND DISCUSSION

Control Performance

The minimum substrate MC in CIM fluctuated with a large range of 43% from maximum saturated MC 85%, while that in MIM was well controlled within a set range of 15% (Fig. Ⅳ-2). Although the daily drainage rate was controlled as 30% at accumulated radiation-based irrigation in CIM, minimum substrate MC decreased to 44% due to continuous changes of environmental factors such as light intensity, cloudiness, and temperature during the growth period. However, substrate MC did not fluctuate as much as in CIM and the minimum substrate MC was maintained at 70% in MIM. Kim et al. (2011) proposed that an irrigation method using drainage level sensors, but it could not directly control the substrate MC within the target range. However the developed irrigation control system used in this experiment could adequately control the substrate MC without increasing. The larger the range of MC variation became, the more salts were integrated in the substrate, resulting in the increase in substrate EC. It can be a factor that prevents water absorption by plant, eventually, it can act as drought stress on plant (Ben-Gal et al., 2008). In Fig. Ⅳ-3, real changes in substrate MC were not shown because it was too complicated to see in graph. Minimum substrate MC 70% means the MC increased up to 85% when irrigated and maintained at 70% after decreased.

Substrate EC was well controlled within 2.5-4.6 $dS \cdot m^{-1}$ in MIM, while increased up to 7.9 $dS \cdot m^{-1}$ instantaneously in CIM (Fig. Ⅳ-3). Irrigation was set start when the substrate EC increases over 4.5 $dS \cdot m^{-1}$ for the purpose of rinsing the accumulated salts in substrate, however, only 15 times of the total irrigation events of 1645 times were conducted by the control function of substrate EC. And it was less than 1%. It was confirmed that root-zone environments were well controlled in the optimum range by applying the criteria for substrate MC and additional substrate EC control in MIM.

Vegetative Growth

Number of nodes and LAI increased with plant growth, however, there was no significant difference in vegetative growth between CIM and MIM. Average values were apparently a little higher in MIM (Fig. Ⅳ-4-A and B). For instance, the rate of increase in number of nodes in MIM (0.09 nodes/day) was faster than that at CIM (0.08 nodes/day) during DAS 180-368 (Fig. Ⅳ-4-A). Until DAS 180, the environmental factors such as radiation and temperature might be insufficient for paprika cultivation because of winter season cultivation. Therefore, these conditions were applied to both MIM and CIM, but the difference in irrigation method was more sensitively affecting the growth of paprika after DAS 180 than before. In both CIM and MIM, the plants were grown within the range of normal growth rate as suggested as 1-node increase every 5-7 days (Hellemans, 2006; Penaloza et al., 1996).

Like the increase in number of nodes, the increase in LAI also tended to be higher in MIM than in CIM with time (Fig. Ⅳ-4-B). The rate of increases in LAI in late growth stage became lower than in early stage in CIM and MIM unlike the increase in number of nodes. It was considered to be due to pruning, leaf senescence of lower leaves (Carvalho et al., 2011a), and weakness of vegetative growth after flower bud initiation (Hellemans, 2006). Due to insufficient lights, SPAD value of lower leaves was clearly lower than that of upper leaves (data not shown).

Both fresh and dry weights of shoots except fruits in MIM were 292.40 and 72.14 g·plant^{-1}, respectively, which were significantly higher than those in CIM during experimental period, while there was no significant difference in fruit between MIM and CIM (Table Ⅳ-2). Due to sufficient water supply, the fresh weight of the shoots in MIM was improved by about 18% compared to CIM, however, there was no difference in water content of the shoots in the end of the experiment. This result explains that all the absorbed water by the plants was used for transpiration (Giuliani et al., 2013; Kim and Lieth, 2003; Ren et al., 2005).

Reproductive Growth

Number of fruits steadily increased in response to plant growth, however, there was no significant difference in regenerative growth between CIM and MIM. Average 3 fruits were more in MIM than in CIM (Fig. Ⅳ-5). The ratio of fallen fruit was less than 10% of the overall in commercial farm where experiment conducted. Harvested average fruit fresh weight and dry weight were 139.76 ± 34.28 and 38.29 ± 4.38 g in MIM, respectively, whereas those in CIM were 121.31 ± 30.46 and 36.40 ± 5.21 g, respectively (Table Ⅳ-2). There were no significant differences in fruit weight and fruit production between

MIM and CIM, however, fruit weight in MIM tended to be higher compared to those in CIM, and water content of fruit also higher in MIM than in CIM.

It was generally reported that fruit MC also similarly increased when sufficient water was supplied and enough transpiration occurred by plants (Diaz-Perez, 2013; Fernandez et al., 2005; Karam et al., 2011; Moreshet et al., 1999). As fruit MC is closely related to sugar content, it can be an important factor in determination of fruit quality (Albuquerque et al., 2012; Liu et al., 2012; Moreshet et al., 1999). In this study, sugar contents in CIM and MIM were 9.1 ± 0.6 and 9.2 ± 0.6, respectively (Table Ⅳ-2). Since there was no significant difference in sugar content between both irrigation methods, it was considered that the sufficient water supply by MIM did not directly affect the fruit quality but contribute to the increase in plant growth.

Relationship among Accumulated Irrigation, Transpiration, and Drainage Amounts

Water amounts of 180.95 and 164.67 L·plant^{-1} were supplied in MIM and CIM during experimental period, respectively, and about 9.9% was more in MIM (Fig. Ⅳ-6). However, drainage did not increase in proportion to the supplied water amounts. That is, the difference in drainage amount was 7.9% when the difference in irrigation amount was about 9.9% between two irrigation methods. Transpiration amounts were 122.60 and 110.59 L·plant^{-1} in MIM and CIM, respectively, and 11.0% more in MIM (Fig. Ⅳ-6). Although, more water were required in MIM, water use efficiency of shoot fresh weight and fruit production to transpiration amount in MIM were higher than those in CIM

(Table Ⅳ-3). In particular, water use efficiency of fruits which closely related to income of farmer increased by 3.7%.

Despite of more water supply, drainage did not increase in proportion to irrigation amount in MIM, which was supposed to be an appropriate moisture control in substrate for reducing plant water stress and driving more water uptake by plants (Ben-Gal et al., 2008; Karam et al., 2011; Kurunc et al., 2011). In addition, transpiration rate also increased by adjusting irrigation interval through compensation of accumulated radiation (Shin et al., 2014b). Additional water supply in MIM compared to CIM could be considered to improve transpiration by leaching concentrated nutrients and lowering EC in substrate (Havrda et al., 1989; Nesmith et al., 1992). Improvement of productivity as shown in Fig. Ⅳ-5 was assumed from the result of promoted vegetative growth (Kurunc et al., 2011). Thus, it is considered that MIM can improve transpiration amount as well as adequate root-zone environments.

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Table Ⅳ-1. Treatments of conventional irrigation method (CIM) and modified irrigation method (MIM).

Irrigation method	CIM[z]		MIM[y]	
Irrigation operating time	Sunrise - 15:30		Sunrise - 15:30	
Irrigation interval (Irrigation start)	Single variable		Multi variables	
	Accumulated radiation	100 $J \cdot cm^{-2}$	Accumulated radiation	Compensated 100 $J \cdot cm^{-2}$
			Substrate MC	70%
			Substrate EC	4.5 $dS \cdot m^{-1}$
Irrigation amount (Irrigation stop)	Single variable		Multi variables	
	1 $dose \cdot event^{-1}$	110 $ml \cdot plant^{-1}$	1 dose	110 $ml \cdot plant^{-1}$
			Substrate MC	85%
			Substrate EC	2.5 $dS \cdot m^{-1}$

[z]CIM : accumulated radiation was used as an irrigation index
[y]MIM : compensated value of accumulated radiation as well as precise controls of substrate moisture content (MC) and electrical conductivity (EC) were used for irrigation control.

Table Ⅳ-2. Fresh, dry weights and water content of shoot and fruit, and sugar content of fruit at conventional irrigation method (CIM) and modified irrigation method (MIM).

Treatment	Shoot			Fruit			
	Fresh weight (g/plant)	Dry weight (g/plant)	Water content (%)	Fresh weight (g/fruit)	Dry weight (g/fruit)	Water content (%)	Sugar content (%)
CIM[z]	1611.33[y]	392.23	75.7	121.31	36.40	70.0	9.1±0.6
MIM	1903.73	464.37	75.6	139.76	38.29	72.6	9.2±0.6
Significance	*[x]	*	NS	NS	NS	NS	NS

[z]See Table Ⅳ-1.

[y]Mean seperation within columns by t-test at P=0.05.

[x]NS,* Nonsignificant or significantly different at P=0.05, respectively.

Table Ⅳ-3. Water use efficiency at conventional irrigation method (CIM) and modified irrigation method (MIM).

Treatment	Water use efficiency (fresh weight/transpiration)	
	Shoot	fruit
CIM[z]	14.57[y]	1.09
MIM	15.53	1.13
Significance	*	*

[z]See Table Ⅳ-1.

[y]Mean seperation within columns by t-test at P=0.05

[x]* Significantly different at P=0.05.

Fig. Ⅳ-1. An experimental view of paprika cultivation in a commerecial greenhouse (Hwasung 21, Hwasung, Korea).

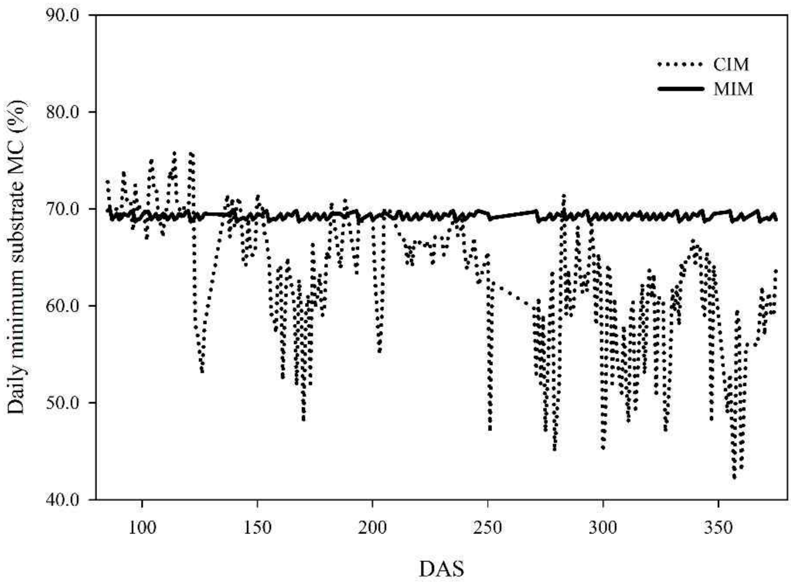

Fig. Ⅳ-2. Comparison of daily minimum substrate moisture content (MC) between conventional irrigation method (CIM) and modified irrigation method (MIM) during experimental period. DAS means days after seeding. See Table Ⅳ-1 for CIM and MIM.

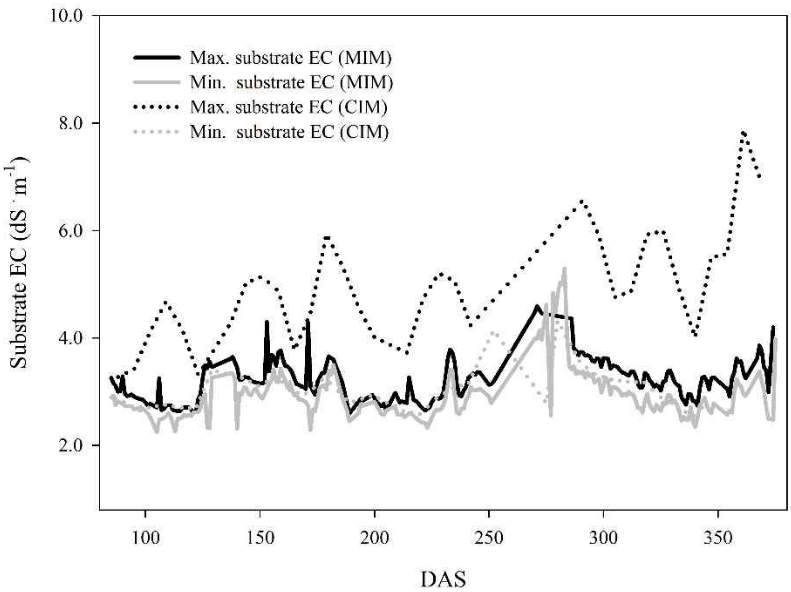

Fig. Ⅳ-3. Change in daily maximum and minimum substrate electrical conductivity (EC) during the experimental period in conventional irrigation method (CIM) and modified irrigation method (MIM). DAS means days after seeding. See Table Ⅳ-1 for CIM and MIM.

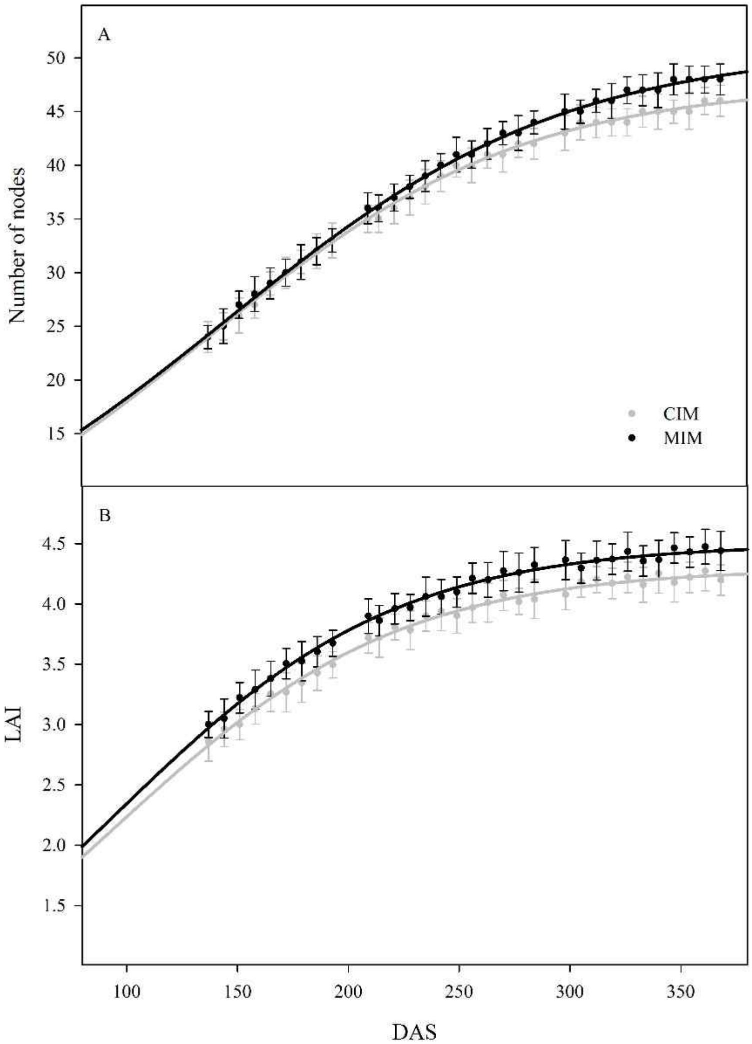

Fig. Ⅳ-4. Change in the number of nodes (A) and leaf area index (LAI, B) during experimental period in conventional irrigation method (CIM) and modified irrigation method (MIM). Vertical bars represent the means ± SE (5 replications). DAS means days after seeding. See Table Ⅳ-1 for CIM and MIM.

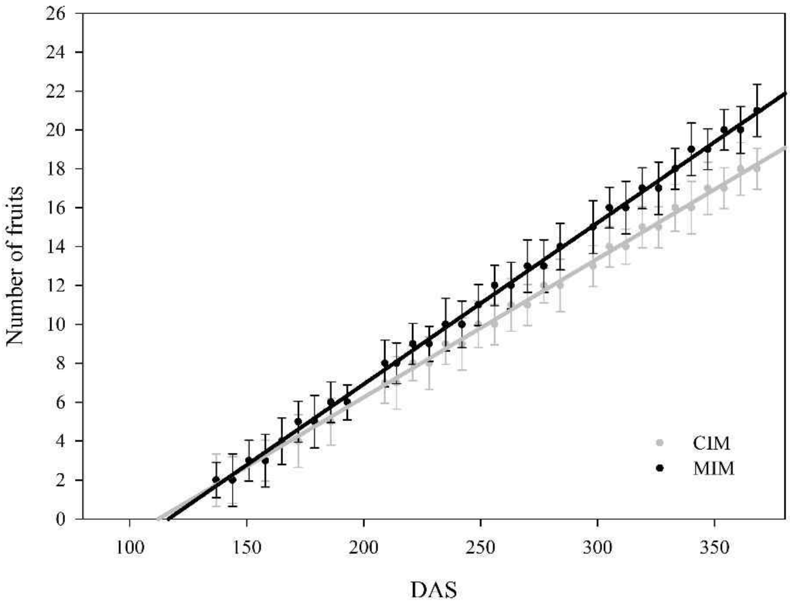

Fig. Ⅳ-5. Change in the number of fruit during experimental period in conventional irrigation method (CIM) and modified irrigation method (MIM). Vertical bars represent the means±SE (5 replications). DAS means days after seeding. See Table Ⅳ-1 for CIM and MIM.

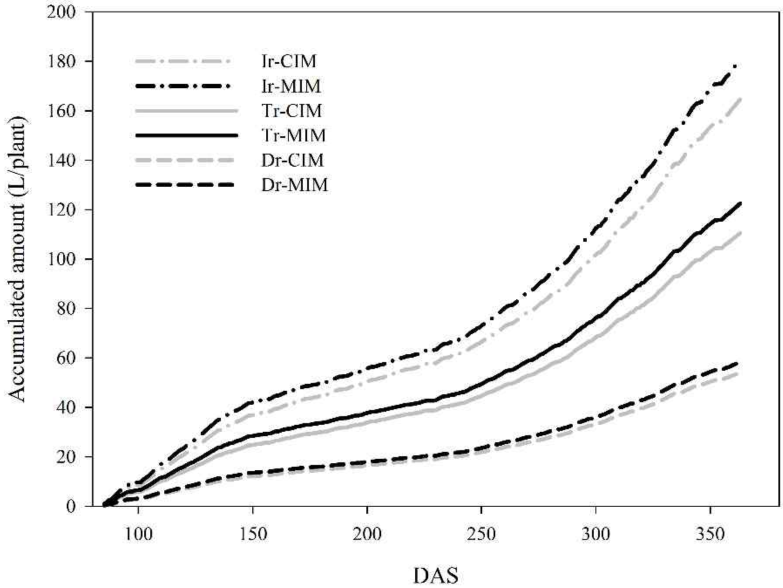

Fig. Ⅳ-6. Accumulated irrigation (Ir), transpiration (Tr), and drainage (Dr) amounts in conventional irrigation method (CIM) and modified irrigation method (MIM) during experimental period. DAS means days after seeding. See Table Ⅳ-1 for CIM and MIM.

CONCLUSIONS

This study focused on development of a precise irrigation control system and evaluation of the developed system. In chapter Ⅰ, continuous transpiration was monitored and precise irrigation suitable for various environments was controlled through the developed irrigation system in paprika cultivation. Through the system, plant water use was estimated and substrate EC was maintained within optimum range. In addition, waste water could be reduced by optimal irrigation with minimizing drought stress on paprika plants. Instantaneous transpiration responses to aerial and root-zone environment were monitored in chapter Ⅱ and Ⅲ, respectively.

A relationship between the transpiration rate and light intensity was determined by continuous transpiration measurement at intervals of 10 min or less within 5% errors in chapter Ⅱ. Based on this relationship, compensated equation for radiation accumulation was suggested to determine the irrigation frequency. The calculated levels of accumulated radiation were adjusted to reflect their quantitative effect on actual transpiration rates. By applying the calibrated light intensity to irrigation control, excessive water and nutrients could be reduced without any negative effect on plant growth.

In chapter Ⅲ, the relationship among transpiration rate, substrate MC, and substrate EC were clarified. Substrate EC had a greater effect on transpiration than substrate MC and showed an inverse relationship with substrate MC. Sufficient water condition could minimize the plant water stress and improved the fruit quality. And frequent irrigation with a small fluctuation of substrate

MC could save more water. From the results, it was found that transpiration and plant growth were improved with the developed system compared to the conventional irrigation system.

Finally, in chapter Ⅳ, the performance of the developed system (chapter Ⅰ) with the irrigation strategies (chapter Ⅱ and Ⅲ) were evaluated at a large-scale commercial farm. Substrate MC and EC were well-controlled within the set ranges of 70-85% and 2.5-4.5 $dS \cdot m^{-1}$, respectively. Through maximizing the water use efficiency by using the precise irrigation control system, transpiration efficiency could be increased by 11% compared to conventional irrigation system. And fruit production was expected to increase by 3.7% with the precise irrigation control system.

In conclusion, the precise irrigation control system with irrigation strategy developed through this study improved fruit productivity and water use efficiency. And the obtained results, measured environmental data, and irrigation strategy can contribute to reduction of production cost as well as improvement of paprika productivity in large-scale commercial farms. In addition, developed irrigation monitoring and control system may be useful in study for searching the optimal environmental conditions according to the plant growth stage by continuously measuring the transpiration response to various environment factors. Also, it is expected that the more sophisticated irrigation strategy in accordance with environmental conditions and plant responses can be established by the system.

ABSTRACT IN KOREAN

본 연구에서는 파프리카 재배에서의 환경제어 요인 중 수분환경을 정밀하게 조절할 수 있는 장치를 제작하고, 지상부와 지하부 환경인자와 파프리카 수분 흡수 반응과의 관계를 구명하여 최적의 수분제어가 가능한 장치를 개발하고자 하였다. 그리고 개발된 장치를 대형 상업농가에 적용하여 성능을 시험하고 정밀 관수 제어의 효과를 구명하고자 하였다.

개발된 정밀 관수제어 장치에서 작물의 수분흡수 반응 지표로 이용된 증산량은 5% 오차 범위 이내에서 10 분 간격으로 측정이 가능하였다. 개발된 장치를 이용하여 증산량을 짧은 시간 간격으로 측정함으로써 계속하여 변화하는 환경요인에 대한 작물의 수분 흡수 반응을 보다 구체화할 수 있었다. 또한 개발된 장치에서 정밀 관수제어를 위한 주요 요소인 근권의 함수율, 근권의 농도, 그리고 관수시 마다의 배액율을 목표하는 기준에 맞추어 자동으로 제어할 수 있었다.

정밀한 증산량의 측정이 가능한 정밀 관수제어장치를 이용하여 다양한 광도에 대해 작물이 실제 이용하는 수분을 정량화 할 수 있었으며, 실제 광도와 증산에 이용되는 광량과의 관계식을 도출하여 관수개시 기준인 광도 누적에 적용하였다. 우리나라와 같이 계절에

따른 광도의 편차가 큰 지역의 특히 여름재배에서 종래의 관수방법에 의한 수분 손실이 크므로 그 효과는 더욱 크게 나타났다.

선행연구의 결과들에서 보여준 것과 같이 근권의 함수율은 근권의 농도와 반비례관계를 보였다. 그리고 순간적인 증산량의 측정을 통하여 근권의 함수율 보다 근권의 농도가 작물의 수분 흡수와 더욱 밀접한 관련이 있음을 알 수 있었다. 이러한 결과로 근권부의 삼투퍼텐셜이 작물의 수분흡수에 큰 저해 요인임을 확인하였다.

환경 요인에 대한 증산반응을 고려한 관수제어 알고리즘이 적용된 정밀 관수제어 장치를 상업농가에 설치하여 성능검증을 실시한 결과, 수분이용 효율이 11% 증가하고, 과실의 생산량은 생체중 기준으로 3.7% 증가함을 알 수 있었다.

본 연구를 통해 개발된 정밀 관수제어 장치를 파프리카 재배에 적용함으로써 과실 생산과 수분이용 효율을 증대시킬 수 있음을 알 수 있었다. 이러한 효과는 재배규모가 커질수록 더욱 커질 것으로 판단된다. 또한 개발된 장치를 이용하여 지금까지 재배자의 경험에 의한 관행의 관수제어방법을 보다 체계화 할 수 있을 것으로 사료된다.