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Original article

Development of a real-time irrigation control system considering transpiration, substrate electrical conductivity, and drainage rate of nutrient solutions in soilless culture of paprika (*Capsicum annuum* L.)

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Summary

As paprika plants (*Capsicum annuum* L.) change their growth state from vegetative to reproductive even in response to 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 environment was required. The objectives of this study were to develop an irrigation control system for accurate monitoring of water consumption by the plants, control the root-zone environment conditions such as drainage rate and electrical conductivity (EC) in substrate, and compare the transpiration amounts estimated by model and measured by the developed system. Environmental factors, such as light intensity, temperature, relative humidity, and EC of nutrient solution were measured. A precise irrigation control system developed was controlled by drainage rate, substrate EC as well as accumulated radiation. A conventional irrigation method based on accumulated radiation (Treatment 1) was compared with the irrigation methods additionally controlling drainage rate (Treatment 2) and both of drainage rate and substrate EC (Treatment 3). Drainage rate and substrate EC were well controlled in the developed system. More water could be saved at Treatment 2. Furthermore, control of substrate EC enabled more precise irrigation control. Productivity of fruits increased at Treatments 2 and 3 than at Treatment 1 without any significant differences in vegetative growth. The transpiration amount could be more accurately obtained by the system than by the model estimation. Particularly, adequate amount of water could be supplied considering multi variables such as accumulated radiation, drainage rate, and substrate EC. By using this system, systemized irrigation strategies can be established and more efficient irrigation management can be possible.

Keywords
drainage control, irrigation frequency, moisture content, precise irrigation, solar radiation, transpiration monitoring

Significance of this study

What is already known on this subject?

- Irrigation systems based on accumulated radiation have been practically used in soilless culture because it was known that the accumulated radiation is proportional to the transpiration of crops.

What are the new findings?

- An irrigation control system was developed in which the transpiration amount was precisely measured and the irrigation strategies considering accumulated radiation, drainage rate, and substrate EC were included. The water use efficiency and fruit productivity of paprika could be improved with this system.

What is the expected impact on horticulture?

- A precise irrigation control strategy considering transpiration and root-zone environments could improve the water use efficiency and crop productivity in soilless culture.

Introduction

Paprika (*Capsicum annuum* L.) is considered a valuable crop worldwide, and its yield and quality are essential factors for economic success. Due to its high sensitivity to environmental conditions, paprika is generally grown in greenhouses where the microclimate can be precisely controlled (Sezen et al., 2006; Ngouajio et al., 2008). Importantly, paprika is known as indeterminate-type plant that can convert from vegetative to reproductive phase 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; Sezen et al., 2006; Ngouajio et al., 2008; 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) have been dominantly applied (Jolliet and Bailey, 1992; Jolliet, 1994; Medrano et al., 2005; Ta et al., 2011). However, the transpiration amount was not always accurately estimated depending on plant species and environmental factors. In addition, a direct sensing of the moisture content of substrate also has been tried for irrigation control (Munoz-Carpena et al., 2005; Pardossi et al., 2009; Zotarelli, 2011). However, it required many sensors and showed low accuracy because of large deviations according to the different measurement points in a large-scale farm, thereby causing unnecessary waste of water or water stress to plants (Pardossi et al., 2009; Pardossi and Incrocci, 2011).

Recently, irrigation methods based on drainage rate or the change in plant weight which reflect the plant water status have been used for management of drought stress (Goldhamer and Fereres, 2001; Jones, 2004; Shelford et al., 2004; Fernández and Cuevas, 2010; Pardossi and Incrocci, 2011). However, the imbalance of drainage during the day caused an undesirable result like salt accumulation in substrate and led to plant stress (Li and Stanghellini, 2001). Although irrigation control systems considering drainage amount were developed by Reddy (1994) and Kim et al. (2011) as single variable, it could not calculate the exact water amount used by plants. Therefore, for better irrigation management, required water amounts and root-zone environmental conditions should be monitored, and irrigation and drainage rates should be finely controlled in soilless culture.

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

Materials and methods

Configuration of the system

The irrigation control system is illustrated in Figure 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 (RAD), temperature, relative humidity, substrate EC and moisture content (MC), 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 the MC of 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 species.

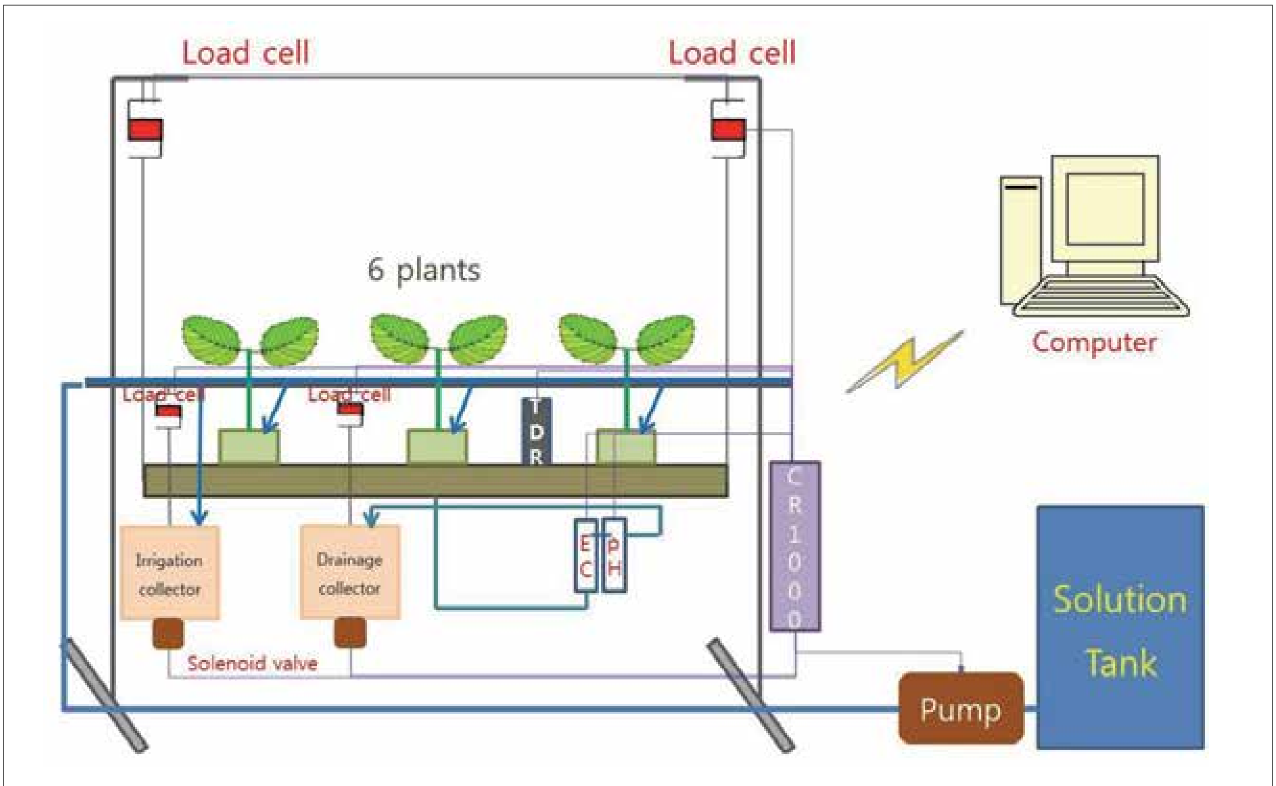

Figure 1. A schematic diagram of the irrigation control system used in this study.

In total, three irrigation control strategies were compared 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, grown on rockwool media (Grotop, Grodan, Roermond, The 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 m^{-1}, the paprika seedlings with 5-6 nodes were transplanted into 0.9 (L) x 0.15 (W) x 0.07 (H) m rockwool slabs (MaXXima, Cultilène, Tilburg, The 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. Concentration of macro elements in nutrient solution included NO_3-N 110 mg L^{-1}, P 50 mg L^{-1}, K 140 mg L^{-1}, Ca 160 mg L^{-1}, Mg 45 mg L^{-1}, and S 60 mg L^{-1}. The EC and pH of the nutrient solutions were maintained at 2.6–3.0 dS 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:

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

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 when calculating the transpiration. Evaporation from substrate was ignored, because it was a very small amount (less than 0.5%) of the total transpiration amount. To compare the measured transpiration of paprika plants, estimated transpiration using environmental factors was expressed by a following modified transpiration model (Baille et al., 1994):

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

where LAI, RAD, and VPD mean leaf area index (m^2 m^{-2}), radiation amount (W m^{-2}), and vapor pressure deficit, respectively. The coefficients a, b, and k were 9.55*e^{-4}, 0.03 (kg d^{-1}), and 0.84, respectively. Since the majority of transpiration occurs during the day, Ta et al. (2011) confirmed the close relationship between the daily transpiration of paprika plants with RAD and LAI without considering the VPD in the model. The values of the parameters in Eq. 2 were obtained by Ta et al. (2011).

Drainage rate was continuously calculated from the amounts of irrigation and drainage. Irrigation frequency and total irrigation amounts were calculated by counting the number and time of pump operations, respectively. The percentage of the water amount used by the plants was calculated from the total water consumption divided by the total irrigation amount supplied per day. Leaf area was calculated by an equation using measured leaf length and width (Park et al., 2009). The variation of substrate EC was monitored, and these measured data were used for control of irrigation. Irrigation pumps were operated based on accumulated 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).

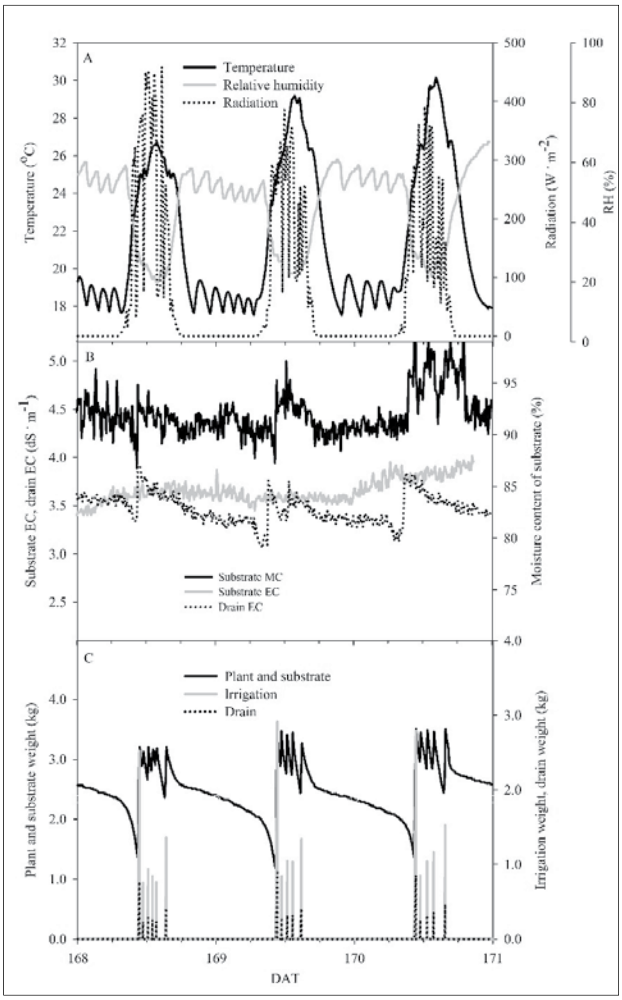

Figure 2. Aerial environmental parameters [temperature, relative humidity, and radiation, (A)], root-zone environmental parameters [substrate moisture content and electrical conductivity (EC), and drainage EC, (B)], and weights [irrigation amount, drainage amount, and weight changes of plant and substrate, (C)] measured in Treatment 2 (168–170 DAT, days after transplanting).

Experimental irrigation treatments

To examine the operation of the system, three irrigation strategies were used (Table 1). In Treatment 1, a conventional irrigation started every time that the accumulated radiation reached 100 J cm^{-2}, and 150 mL of nutrient solution were supplied to each plant at each irrigation pulse. Since drainage rate of 30% during the day was recommended for preventing salt accumulation in substrate (Hellemans, 2006), in Treat-

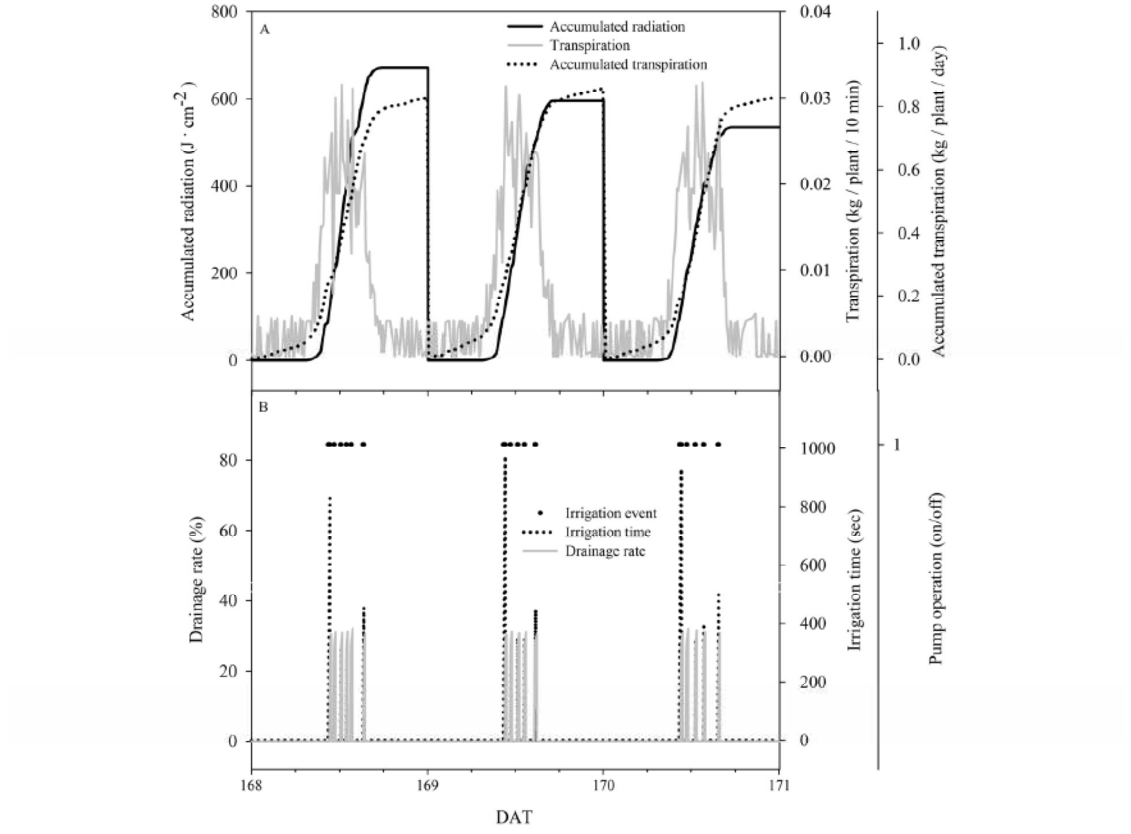

Figure 3. Accumulated radiation, calculated transpiration, and accumulated transpiration (A), and pump operation, irrigation time, and drainage rate (B) in Treatment 2 (168–170 DAT, days after transplanting).

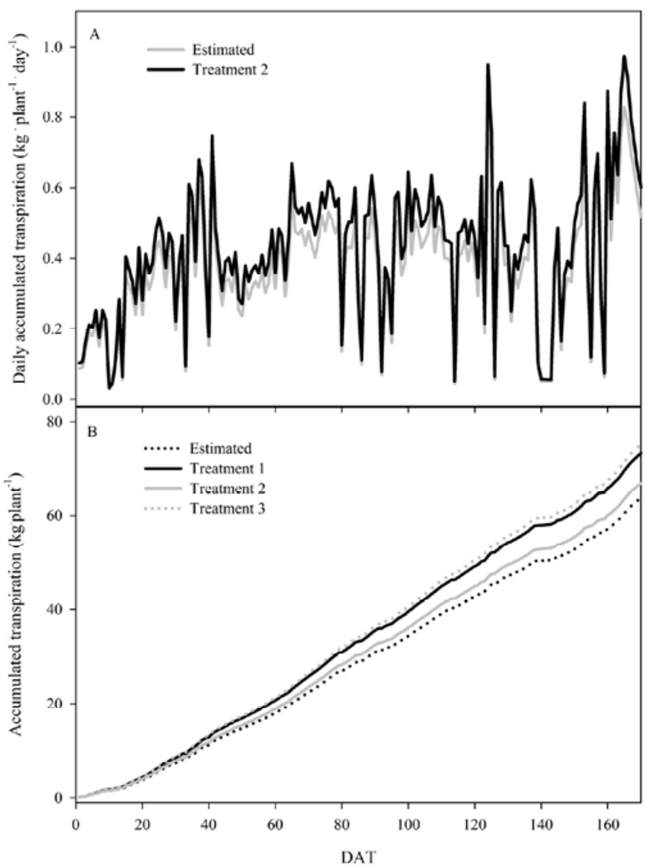

Figure 4. Comparisons of the daily transpiration amounts estimated by transpiration model and measured in Treatment 2 (A), and integrals of the transpiration amounts in the model and Treatments 1, 2, and 3 over experimental periods [1–170 DAT, days after transplanting, (B)].

Table 1. Treatments for three irrigation control strategies.

Treatment no.	Irrigation-on	Irrigation-off
1	Accumulated radiation (every 100 J cm^{-2})	150 mL/dripper/pulse
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}

ment 2, irrigation was initially the same as in Treatment 1 but a stop function of irrigation was added when the drainage rate reached 30% during the irrigation pulse. In Treatment 3, an additional factor of substrate EC was programmed compared to Treatment 2. Even if the accumulated radiation was still lower than the set point, when the substrate EC exceeded 3.8 dS 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 the substrate EC decreased to less than 3.5 dS m^{-1}. The substrate MC was maintained within a suitable range of 40–90% for paprika plants [according to paprika growing manual (Hellemans, 2006)]. The drainage rate of each irrigation pulse and the total number of daily drainage pulse were compared among all irrigation treatments. The fluctuation of substrate EC in Treatment 3 was compared with those in Treatments 1 and 2 to determine the performance of the irrigation systems during experimental periods.

Results and discussion

Consecutive measurements of transpiration

At Treatment 1, conventional irrigation control, the diurnal variations in substrate MC and EC were greater than Treatments 2 and 3. Figure 2 showed sample results under the irrigation strategy based on drainage rate in Treatment 2. From the measured data in Figure 2C, accumulated transpiration amount every 10 minutes was obtained for detail comparison and a close relationship was consistently observed between accumulated radiation and accumulated transpiration (Figure 3A). By using the developed system, the drainage rate was well controlled at approximately 30% for all irrigation pulse (Figure 3B). In fact, deviations in drainage rate were considerable in soilless culture with season and even during the day.

The amount of measured daily transpiration in Treatment 2 was around 15% higher than that estimated by Eq. 2 (Figure 4A). In all three irrigation treatments, the measured amounts of the measured transpiration were higher than that of the estimated transpiration (Figure 4B). The maximum 18% difference between the measured and estimated transpiration amounts was observed in Treatment 3 at the end of the experiment. From the results, it was deduced that the water supplied in the conventional irrigation method by estimation of transpiration amount was lower than the actual water demand of the plants. The lower transpiration amount in Treatment 1 than those in Treatments 2 and 3 as shown in Figure 4B is presumably because the water supply was limited in Treatment 1 compared to those in Treatments 2 and 3.

The accumulated radiation, VPD, and LAI were commonly used as variables in Eq. 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 plant species (Smeal et al., 1991; Hellemans, 2006). 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 direct weighing rather than by estimating with predetermined equations. 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 pulse

Table 2 shows a detail comparison of drainage rate at every irrigation pulse for 3 days (168 DAT to 170 DAT) as a sample case in summer. When the conventional irrigation based on an accumulated radiation of 100 J cm^{-2} was applied, as in Treatment 1, more than 70% of the drainage was concentrated after 12:00 pm (from the third irrigation pulse) because drainage almost did not occur at the first irrigation pulse. However, in Treatment 2 a drainage rate of 30% was maintained at every pulse under the irrigation control. Conversely, the distribution of drainage rate varied more in Treatment 3 compared with Treatment 2, drainage was not concentrated at a certain time of the day as shown in Treatment 1. The highest drainage rate occurred at first irrigation pulse of the day in Treatment 3 for salinity rinsing in substrate. In addition, the first irrigation pulse during the day was supplied at the earliest time in Treatment 3 among the treatments. Due to the control of substrate EC at earlier irrigation pulse in Treatment 3, irrigation pulse tended to be concentrated before 12:00 pm. In fact, drainage control should consider not only the irrigation amount but also the change in substrate EC (Scoggins and Van Iersel, 2006). The larger the 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 and nutrients. Therefore, maintaining regular drainage can reduce the waste of water through excessive irrigation and avoid the drought stress of plants in soilless cultures.

Function of the substrate EC control and efficiency of water usage and plant growth

Water stress by increased substrate EC is one of the major

Table 2. Detail comparisons of irrigation, drainage amount and drainage rate at different irrigation control treatments for 3 days (168–170 DAT, days after transplanting) in summer.

Irrigation pulse		Treatment 1[z]			Treatment 2			Treatment 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 1.

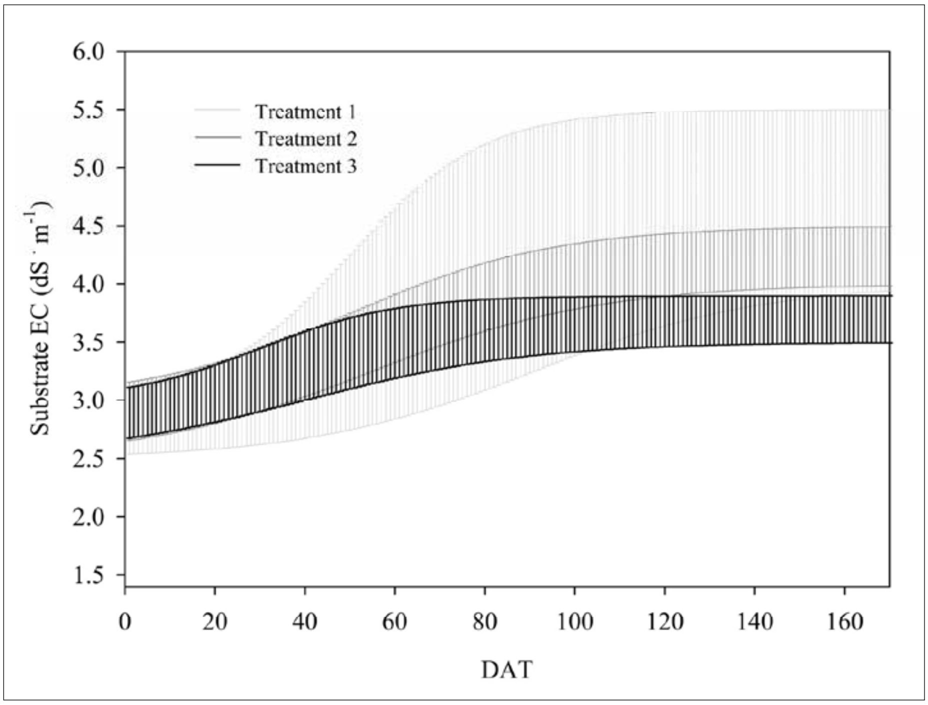

Figure 5. Comparison of substrate electrical conductivity (EC) among Treatments 1, 2, and 3 during experimental periods (1–170 DAT, days after transplanting). Average substrate EC with standard error were 3.98 ± 0.78, 3.77 ± 0.27, and 3.49 ± 0.25 at Treatments 1, 2, and 3, respectively.

factors that interfere with transpiration in plants (Zotarelli et al., 2009). The substrate EC showed a wide range of fluctuation during experimental periods in Treatment 1, ranging from 2.54 to 5.50 dS m^{-1}, while gradually increased to 4.49 dS m^{-1} in Treatment 2 and maintained within the set range of 2.67 to 3.90 dS m^{-1} in Treatment 3 (Figure 5). Considering that the substrate EC is closely related to transpiration amount and substrate moisture content, the rapid increase in substrate EC in Treatment 1 is likely due to insufficient water supply, especially in the morning. Differently, the increased substrate EC in Treatment 2 could be due to insufficient drainage amount rather than 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 words, the drought stress of plants could be more effectively prevented by controlling substrate EC than using the drainage-based irrigation.

Approximately 92.5 kg of water was used for irrigation of a plant in Treatment 1 during experimental periods, while 105.9 and 117.82 kg of water were used in Treatments 2 and 3, respectively. And 24.8, 32.0, and 41.9 kg of drainage occurred in Treatment 1, 2, and 3, respectively (Table 3). From the above data, the percentage of water used by the paprika plants were calculated as 72.3%, 69.2%, and 63.8% of the volume supplied, in Treatments 1, 2, and 3, respectively (Table 3). The percentage of water used was the highest in the conventional irrigation (Treatment 1), most likely because the water supply was insufficient compared to 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 Treatment 3, the substrate EC remained constant regardless that the transpiration amount in Treatment 3 was approximately 13% greater than that in Treatment 1 (Figure 4B). Vegetative growth such as number of nodes, LAI, and fresh weight did not show significant differences among the treatments at the end of the experiment (Table 4). Total number of fruit sets increased and marketable fruit yields decreased with increasing fruit drop rates in Treatment 1 compared to those in Treatment 2 and 3 (Table 4). The average fruit shape (width/height) and sugar content (brix) were 0.7 and 8.5, respectively, with no significant differences among the treatments. More water was used for stable root-zone environment, resulting in the increase in productivity.

From the results, it was considered that the transpiration amount was most likely increased under sufficient irrigation and stable control of root-zone environment. Abu-Awwad (1998) and Hati et al. (2001) reported that the management of substrate EC with sufficient irrigation increased the transpiration amount from vegetable crops. In addition, the total number of leaves increased while the leaf area decreased with increase of substrate EC due to insufficient irrigation (Hati et al., 2001). And the transpiration was decreased with occurrence of plant physiological disorder (Li and Stanghellini, 2001). In this study, the substrate EC could be precisely controlled by increasing irrigation pulse in Treatment 3, but significant increase in water consumption also occurred. For not only preventing excessive water use and but also improving fruit productivity, an optimum range of substrate EC through irrigation control should be investigated in soilless culture of paprika.

Table 3. Comparisons of accumulated irrigation, drainage, transpiration amount, and percentage of water used of paprika growth at different irrigation control treatments (1–170 DAT, days after transplanting).

Treatment no.	Accumulated			Water used (%)
	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 1.

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 pulse 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 (Figure 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 provide adequate irrigation. The data in Treatment 2 in Table 2, for instance, showed that the drainage rate was controlled to fit the set value and also the control function of substrate EC to avoid water stress was well-defined (Figure 5). The radical change of root-zone environment could be controlled by the

Table 4. Comparisons of plant growth and yield at different irrigation control treatments (170 DAT, days after transplanting).

Treatment no.	Vegetative growth			Reproductive growth		
	Number of nodes	LAI (m^2 m^{-2})	Fresh weight (g/plant)	Total number of fruits	Number of marketable fruits	Fruit drop rate (%)
1[z]	31.8 ± 1.2	3.6 ± 0.4	1342.3 ± 78.2	8.7 ± 0.2	6.7 ± 0.2	23.0
2	32.4 ± 0.9	3.7 ± 0.3	1389.2 ± 62.9	7.9 ± 0.1	7.2 ± 0.1	8.8
3	31.9 ± 1.1	3.7 ± 0.5	1410.1 ± 69.8	8.1 ± 0.2	7.2 ± 0.1	11.1
Significance	NS	NS	NS	*	*	*

[z] See Table 1.

[y] Mean ± SE (6 replications).

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

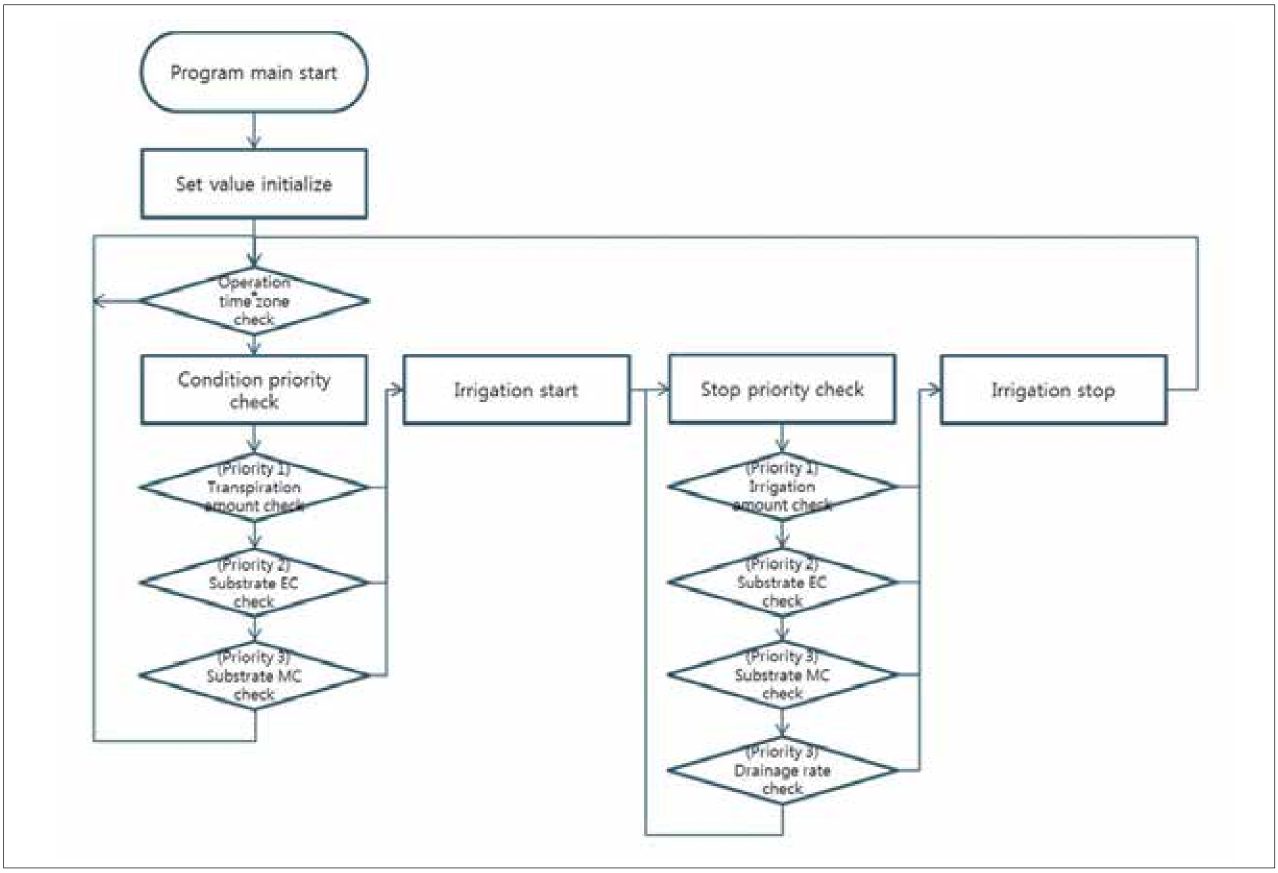

Figure 6. Flowchart of an irrigation control.

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 strategy focused on single variable like drainage (Reddy, 1994; Kim et al., 2011). However, more precise irrigation control could be available considering the combination of variables like accumulated radiation, drainage rate, and substrate EC.

Conclusions

A continuous monitoring of transpiration and precise irrigation control system suitable for paprika plants was developed. The daily transpiration amount precisely obtained with the developed system was maximum 15% higher than that estimated by transpiration model. A drainage rate of 30% could be maintained at every irrigation pulse without biased concentration at a certain time of the day. In addition, drought stress of the plants could be more effectively controlled by the irrigation with management of substrate EC than the drainage-based irrigation. With the developed system, systemized irrigation strategy with efficient irrigation management can be possible with improvement of productivity and quality and the relationship between water consumption by plants and various environmental factors could be clarified.

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