Protected Horticulture and Plant Factory, Vol. 22, No. 3:248-255, September (2013)
DOI http://dx.doi.org/10.12791/KSBEC.2013.22.3.248
pISSN 2288-0992
eISSN 2288-100X

Scheduling Non-drainage Irrigation in Coir Substrate Hydroponics with Different Percentages of Chips and Dust for Tomato Cultivation using a Frequency Domain Reflectometry Sensor

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Abstract. This study examined an automated irrigation technique by a frequency domain reflectometry (FDR) sensor for scheduling irrigation for tomato (*Solanum lycopersicum* L. 'Starbuck F1') cultivation aimed at avoiding effluent from an open hydroponic system with coir substrate containing different ratios of chip-to-dust (v/v) content. Specifically, the objectives were to undertake preliminary measurements of irrigation volumes, leachate volume, volumetric water content and electrical conductivity (EC) in the substrate, plant growth, fruit yield, and water use efficiency resulting from variation in chip content as an initial experiment. Commercial coir substrates containing different percentages of chips and dust (0 and 100%, 30 and 70%, 50 and 50%, or 70 and 30%), two-story coir substrates with different percentages of chips in the lower layer and dust in the upper layer (15 and 85%, 25 and 75%, or 35 and 65%), or rockwool slabs were used. The results showed that a negligible or no leachate was found for all treatments when plants were grown under a technique for scheduling non-drainage irrigation using a frequency domain reflectometry (FDR) sensor. Daily irrigation volume was affected by chip content in both commercial and two-story slabs. The highest plant growth, marketable fruit weight, and water-use efficiency were observed in the plants grown in the commercial coir slab containing 0% chips and 100% dust, indicating that the FDR sensor-automated irrigation may be more useful for tomato cultivation in coir substrate containing 0% chips and 100% dust using water efficiently and minimizing or avoiding leachate and thus increasing yield and reducing pollution. Detailed experiment is necessary to closely focus on determining appropriate irrigation volume at each of irrigation as well as duration of each individual irrigation cycle depending on different physical properties of substrates using an automated irrigation system operated by the FDR sensor.

Additional key words: leachate volume, two-story slab, volumetric water content, water use efficiency

Introduction

Drainage produced by a hydroponic growing system causes environmental pollution with loss of water and nutrients (Choi et al., 2001). Environmental and economic concerns regarding nutrient contamination are growing (Giuffrida et al., 2003), and in the Netherlands, the leaching of drain water from greenhouses into the soil has been prohibited to protect the quality of groundwater (Runia and Amsing, 2001). As a result, there is a need for the development of a drainage-free open hydroponic system suitable for a particular substrate, for which irrigation volume and timing has to be managed depending on the water requirements of the crop to avoid leaching of nutrient-rich solution. Efficient irrigation management can allow growers to reduce leaching and runoff and to improve plant growth. Bilderback (2000) suggested that efficient irrigation is a straightforward and inexpensive way to reduce leaching and runoff from container production. Utilizing a soil-moisture sensor to monitor substrate water content was successful in both greenhouse and nursery cultivations (Burnett, 2008; van Iersel et al., 2010). Lin (2003) showed that frequency domain analysis increases the accuracy of the data by permitting increases in the bandwidth. For this reason, the FDR system has more potential than the travel time analysis methods with time domain reflectometry (TDR). Soil moisture sensor based on the FDR is capable of monitoring both electrical conductivity (EC) and soil water content. Hilhorst (2000) presented a linear relationship between bulk electrical conductivity and dielectric constant in moist soil, in which using this linear relationship, measurements of pore water electrical conductivity

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Received July 21, 2013; Revised August 14, 2013;
Accepted August 28, 2013

can be made in a wide range of soil types without soil-specific calibrations.

The popularity of coir is increasing worldwide for greenhouse crops (Noguera et al., 2000). It is an organic substrate obtained after the extraction of fiber from the husk of coconut (*Cocos nucifera* L.) fruit (Abad et al., 2002). As with most of the hydroponic substrates, coir has a larger particle size and releases more water at much lower pressure than most soil types. The bulk density of coir varies between 0.04 and 0.13 kg m^{-3}, depending on the ratio of chips to dust (Evans et al., 1996; Kang et al., 2004). The addition of coconut chips to coconut dust increases the air-space and reduces the easily available water content (Prasad, 1997). However, this information does not provide irrigation strategy in moisture sensor controlled irrigation system for commercial production. Therefore, the purpose of this study was to examine a technique for scheduling irrigation using the FDR sensor aimed at avoiding effluent from an open hydroponic system with coir substrate containing different percentages of chips and dust, two-story coir substrates with different percentages of chips in the lower layer and dust in the upper layer, and commercial rockwool substrate. The key objectives were to undertake preliminary measurements of irrigation volumes, volumetric water content and electrical conductivity (EC) in the substrate, growth and fruit yield of tomato, and water use efficiency resulting from variation in chip content as an initial experiment.

Materials and Methods

1. Plant growth and conditions

This experiment was undertaken in a heated polyethylene film greenhouse at KonKuk University, Chungju, Chungcheongbuk-do, located at latitude 35°49'N and longitude 127°08'E. Tomato seed (‘Starbuck F1’, De Ruiter Seeds®.) was sown on February 1, 2012, and four tomato seedlings were transplanted on March 16, 2012, in each commercial coir slab (100 × 20 × 10 cm, chip : dust (v/v) = 0 : 100%, 30 : 70%, 50 : 50%, or 70 : 30%, Sivanthi Joe Coirs, Tamil Nadu, India), in each two-story coir slab with different percentages of chips in the lower layer and dust in the upper layer (chip : dust (v/v) = 15 : 85%, 25 : 75%, or 35 : 65%), or in each rockwool slab (UR Co. Ltd., Korea) as a control with 1.2 m between rows and 0.33 m between plants. Before the transplant, the coir slabs were washed with tap water at approximately pH 6.2 and EC 0.15 dS m^{-1} until the EC value of the slabs reached 0.3 dS m^{-1}. Four coir slabs per treatment were placed in a heated polyethylene film greenhouse at KonKuk University. A FDR sensor (WT1000N, Mirae-Sensor®, Korea) with a three-rod probe 65 mm long was placed vertically in the slabs per treatment. A nutrient solution at pH 5.8 and EC 2.0 dS m^{-1} was supplied using a drip irrigation system after transplant. The nutrient solution (Glasshouse Crops Research and Experiment Station at Naaldwijk, Netherlands) was supplied from a 125-L tank containing a water pump (55W, Hyupsin®, Korea). The composition of the nutrient solution was as follows: 13.75 me L^{-1} nitrate nitrogen (NO_3-N), 1.25 me L^{-1} ammonium nitrogen (NH_4-N), 3.75 me L^{-1} phosphorous (P), 8.75 me L^{-1} potassium (K), 8.5 me L^{-1} calcium (Ca), 4.0 me L^{-1} magnesium (Mg), 7.5 me L^{-1} sulfur (S), 0.84 ppm iron (Fe), 0.55 ppm manganese (Mn), 0.33 ppm zinc (Zn), 0.05 ppm copper (Cu), 0.33 ppm boron (B), and 0.05 ppm molybdenum (Mo). The amount of water irrigated and drained was measured daily until the July 12, 2012. During the study, the temperature, relative humidity, carbon dioxide (CO_2) concentration, and photosynthetically active radiation (PAR) were recorded every 30 minutes using an ALMEMO® 2890-9 device (AHLBORN, Holzkirchen, Germany), which has both data processing and compiler systems. Some data gathered by the ALMEMO data compiler were transferred to a computer using a Universal Serial Bus (USB).

2. Automated irrigation system using the FDR sensor

The automated irrigation system using the FDR sensor was applied after transplanting. Calibration of the FDR sensor to measure water content was carried out using glass beads. The beads were gradually mixed until saturation with different pore water solutions ranging from distilled water up to solutions with an EC of 3.0 dS m^{-1}. When the volumetric water content in the coir substrate reached experimental set trigger points, the irrigation was automatically initiated. Each irrigation amount was 60 mL per plant. The water sensor avoided irrigation when the stop set point of substrate moisture was already present. The start and stop frequency values were manually input. For example, irrigation was started from < 50% value, and stopped at < 55% for the 50% treatment. Irrigation-on-and-off hours were modified depending on daily times of sunrise and sunset. Irrigation began 1 hour after sunrise,

Table 1. Summary of periodically changes in daily duration of irrigation and targets of volumetric water content of coir substrate controlled by the FDR after transplanting at 16th of March 2012.

Days	DAT (days after transplant)	Daily duration of Irrigation	Targets of volumetric water content
16th March~10th April	0~25	9:00~15:00	50%
11th April~7th May	26~52	9:00~15:00	53%
8th May~15th May	53~60	7:00~17:00	55%
16th May~17th May	61~62	7:00~17:00	57%
18th May~21th May	63~66	7:00~17:00	60%
22th May~14th June	67~90	7:00~17:00	67%
15th May~26th June	91~102	7:00~17:00	65%

and ended 3 hours before sunset, or at 9:00 a.m. and 3:00 p.m., respectively, between 0 and 52 days after transplant (DAT) (between the March 16 and May 7, 2012), and at 7:00 a.m. and 5:00 p.m. between 53 and 102 DAT (between the May 8 and June 26, 2012). The volumetric water content level was preset at 50% between 0 and 25 DAT, 53% between 26 and 52 DAT, 55% between 53 and 60 DAT, 57% between 61 and 62 DAT, 60% between 63 and 66 DAT, 67% between 67 and 90 DAT, and 65% between 91 and 102 DAT (Table 1). The data of volumetric water content, EC, and temperature in the root zone of the substrate were saved every 10 minutes in a data logger (WT600, Mirae-Sensor®, Korea) connected to the sensors. The data were then downloaded and analyzed using an Excel spreadsheet. The water content of the substrate monitored by the FDR sensor was quantified as the internal capacitance of the substrate using high-frequency pulses, while the EC value was quantified as both the internal capacitance and resistance value using low-frequency multiple pulses, which allows measurement of both the water content and ion concentration in the substrate at the same time. The voltage values for the water content and ion concentration were calculated by assessing different numbers of high-frequency pulses returned after converting the high-frequency pulse into direct current (DC) in a current-conversion circuit by a matching transmitter set between antennae and oscillators of a high-frequency pulse. In addition, the conductivity sensor was temperature corrected.

3. Water use efficiency

The water use efficiency (WUE) was calculated as a function of the applied irrigation water retained in the substrate [WUE = leaf, stem and fruit fresh weight at harvest ÷ (applied irrigation volume-leachate)].

4. Statistics

Data were subjected to analysis of variance (ANOVA) with SAS 9.2 (SAS Institute, Cary, North Carolina, USA). The experiment was set up using a randomized complete block design for four replications. Mean separation of measurement variables used Duncan's Multiple Range Test (DMRT) at the 5% level.

Results

1. Growth conditions

During the study, the average air temperature was 27°C ranging from 17 to 37°C, relative humidity from 30% to 99%, CO_2 concentration from 200 to 700 ppm, and PAR from 0 to 1180 $\mu m \cdot m^{-2} \cdot s^{-1}$. During the night, from 22:00 to 6:00, the CO_2 concentration inside the greenhouse was higher than 600 ppm, while the lowest concentration of CO_2 was measured at 13:00, about 300 ppm. During the entire growth period, the lowest temperature was approximately 17°C and generally remained higher than the outside temperature. Relative humidity during the night and early morning between 8:00 p.m. and 6:00 a.m. ranged from 80% to 99%, while it ranged from 50% to 70% during the day. The highest PAR level was at 13:00 in the 26th of June at 1180 $\mu m \cdot m^{-2} \cdot s^{-1}$ (data not shown).

2. Irrigation and leachate volumes

Significantly higher daily average irrigation amounts and total irrigation volume for 75 days were observed in the slabs including about 25 to 30% chips in both commercial and two-story slabs. The highest daily average irrigation amounts per plant, 2.422 L and 2.495 L, were found between 24 and 99 DAT when plants were grown in the commercial slab with 30% chips and 70% dust and grown in the two-story coir slab with 25% chips in the lower layer

Table 2. Daily average irrigation volume (mL $plant^{-1}$ day^{-1}) (n = 75), total irrigation volume (n = 2), and total leachate volume (n = 2) measured from 24 to 99 days after transplant as affected by the percentage of chips and dust in coir substrate controlled by the frequency domain reflectometry (FDR).

Substrates	Ratio (chip : dust)	Daily-averaged Irrigation volume (mL $plant^{-1}$ day^{-1})	Total irrigation volume for 75 days (L $plant^{-1}$)	Total leachate volume for 75 days (L $plant^{-1}$)
Commercial slab	Rockwool	2109 bc	153bc	0
	0 : 100	2129 bcd	160abc	0
	30 : 70	2422 a	182ab	0.22 (± 0.25)[Z]
	50 : 50	2279 abc	171ab	0.53 (± 0.29)
	70 : 30	1858 c	139c	1.45 (± 0.68)
Two-story slab	15 : 85	2079 bc	156bc	2.28 (± 0.88)
	25 : 75	2495 a	187a	2.32 (± 0.96)
	35 : 65	2396 ab	171ab	1.91 (± 0.72)

[Z]: standard deviation for two replications.
Means within columns sharing the same letter are not significantly different by Duncan's Multiple Range Test (DMRT) at $P < 0.05$.

and 75% dust in the upper layer, respectively (Table 2). In contrast, the lowest daily average irrigation amount and total irrigation volume for 75 days was 1.858 L and 139 L, respectively, when plants were grown in the commercial slab with 70% chips and 30% dust. The results of daily average irrigation volume and total irrigation volume for 75 days in the rockwool substrate are the same as those for the slabs including 0% chip in commercial slab and 15% chips in two-story slab. There was no leachate from either the commercial slab with 0% chips and 100% dust or the rockwool slab during the growing period, and all treatments had a negligible amount of leachate volume.

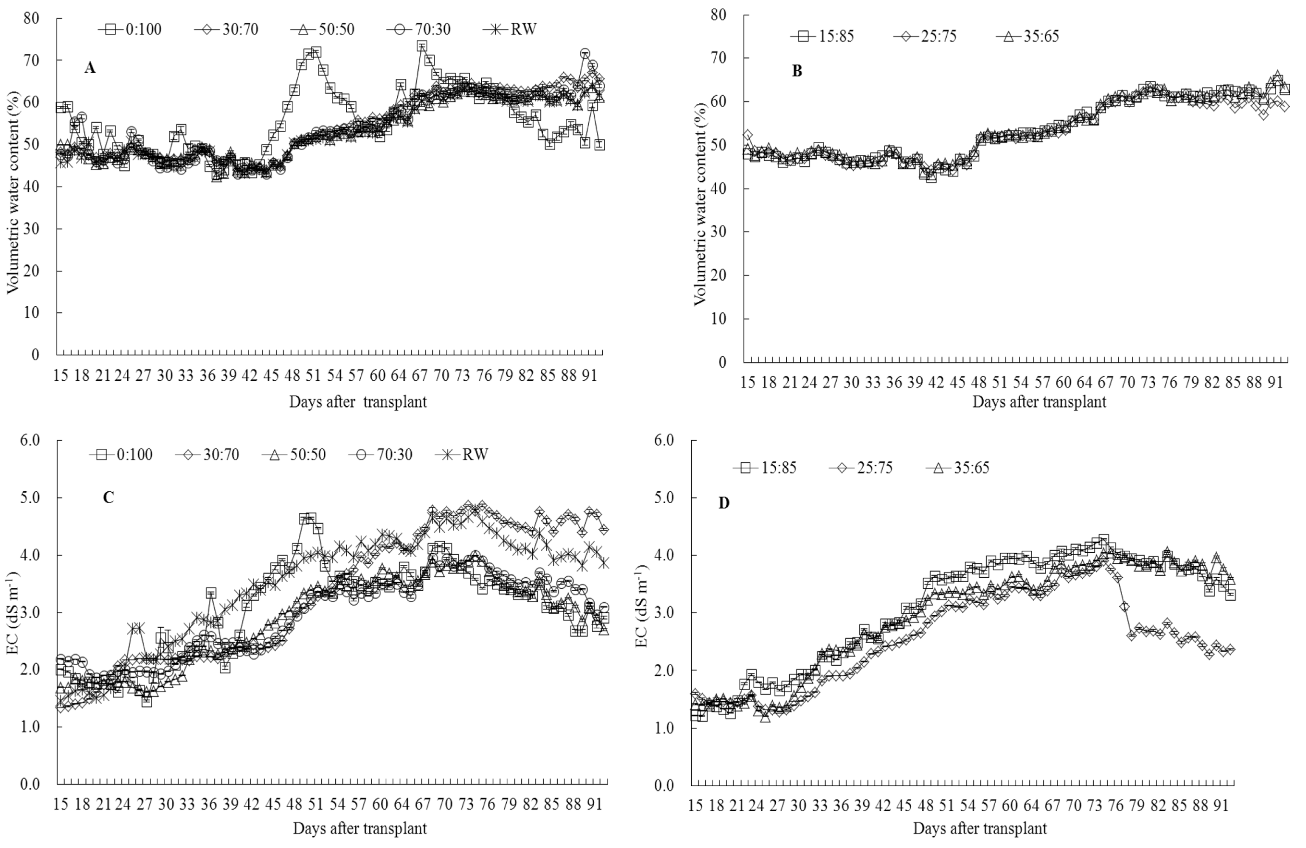

Fig. 1. Change of volumetric water content and electrical conductivity (EC) levels measured by the FDR sensor in the commercial coir slab (A, C) and in the two-story substrate (B, D) when the water content of the substrate was controlled between 55% to 60% and the EC of the nutrient solution was supplied at 2.0 dS m^{-1}. Thirty observations were made between 15 and 92 days after transplant (DAT).

Table 3. Plant height, fresh weight of leaf and stem, and leaf number per plant of tomatoes grown hydroponically for 70 days after transplant as affected by the percentages of chips and dust in coir substrate controlled by the FDR.

Substrates	Ratio (chip : dust)	Plant height (cm)	Leaf fwt. (g)	Stem fwt. (g)	Leaf number (no)
Commercial slab	0 : 100	195 a	1718 a	628 a	29.25 a
	30 : 70	186 a	1495 ab	571 ab	28.13 a
	50 : 50	177 ab	1171 c	510 b	27.75 a
	70 : 30	179 ab	1231 bc	563 ab	28.33 a
	Rockwool	168 b	1575 a	570 ab	29.29 a
Two-story slab	15 : 85	182 ab	1488 ab	579 ab	28.25 a
	25 : 75	189 a	1465 ab	554 ab	29.00 a
	35 : 65	190 a	1615 a	626 a	28.50 a

Means within columns sharing the same letter are not significantly different by Duncan's Multiple Range Test (DMRT) at $P < 0.05$.

3. Volumetric water content and EC level of substrate

The volumetric water content reached between 50% and 70% for both commercial and two-story slabs. The volumetric water content in the commercial slab with 0% chips and 100% dust showed more fluctuation during the observation period compared to that in other slabs (Fig. 1A). The substrate EC concentration ranged between 1.5 and 4.8 dS m^{-1} that started increasing from 30 DAT and decreasing from 75 DAT. The commercial slab with 30% chips and 70% dust and the rockwool slab had slightly higher EC concentration (Fig. 1C, D).

4. Plant growth

The fresh weights of leaf at 102 DAT showed a significant reduction in plants grown in the commercial slab with 50% chips and dust and with 70% chips and 30% dust (Table 3). Significantly higher fresh weights of leaf and stem and leaf number were found in the plants grown in the commercial slab with 0% chips and 100% dust as well as those grown on the two-story coir slab with 35% chips in the lower layer and 65% dust in the upper layer. There were no significant differences in photosynthetic rates and stomata conductance for all the treatments (data not shown).

5. Fruit yield and quality

The fruit weight and fruit numbers were significantly affected by the percentages of chips and dust in the slabs. The weights of marketable fruits grown in the commercial slab with 50% chips and dust and 70% chips and 30% dust or on rockwool were significantly lower than those in other treatments, while the highest soluble solid content was observed in fruits from the slabs; on average they were 7.0 Brix (Table 4). The highest fruit weights and fruit numbers were observed in the plants grown in the commercial slabs with 0% chips and 100% dust.

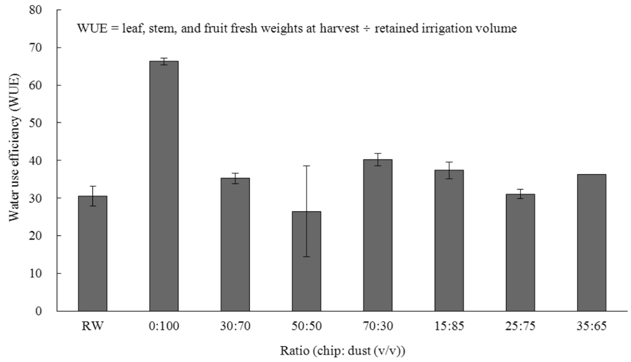

Fig. 2. Water use efficiency (WUE = leaf, stem, and fruit fresh weight at harvest ÷ retained irrigation volume) of tomato grown hydroponically as affected by the percentage of chips and dust in coir substrate controlled by the FDR. Bars indicate standard errors (±) of means for three replications per treatment.

6. Water use efficiency

Water use efficiency (WUE) decreased as plants were grown in substrate with higher chip content (Fig. 2). The highest WUE was observed in the commercial slab at 0% chips and 100% dust.

Discussion

A negligible or no leachate was found for all treatments when plants were grown under a technique for scheduling non-drainage irrigation using the FDR sensor (Table 2). These results indicate that irrigation scheduling for the non-drainage hydroponic system using a FDR sensor is very precise and effective and increases sustainability. Our previous study showed that scheduling irrigation using a frequency domain reflectometry (FDR) sensor at a volumetric

Table 4. Marketable fruit (> 150 g fruit^{-1}) weights per plant, marketable fruit numbers per fruit, and soluble solid contents of tomatoes harvested from the first to fifth cluster grown hydroponically as affected by the percentages of chips and dust in coir substrate controlled by the FDR.

Substrates	Ratio (chip : dust)	Marketable Fruit weights (g) (n = 8)	Marketable Fruit weight (g) (n = 180)	Soluble solid content (°Brix)
Commercial slab	0 : 100	8251 a	285 a	5.63 b
	30 : 70	4131 b	275 a	5.78 b
	50 : 50	2905 de	200 c	7.05 a
	70 : 30	3297 cd	214 bc	7.03 a
	Rockwool	2407 e	209 bc	6.85 a
Two-story slab	15 : 85	3679 bc	272 a	6.92 a
	25 : 75	3453 bcd	249 ab	6.69 a
	35 : 65	3782 bc	271 a	6.34 ab

Means within columns sharing the same letter are not significantly different by Duncan's Multiple Range Test (DMRT) at $P < 0.05$.

water content between 50% and 60% produced no leaching of drain water from the coir substrate hydroponic system without water stress conditions over the entire investigation period during the autumn to winter season, and also suggested that efficient irrigation scheduling to obtain a drainage-free system during the late-spring to summer season can be achieved by first controlling the volumetric water content of the substrate to between 40% and 50% by the FDR, and then increasing it to between 60 and 70% with close observation of water content patterns and the electrical conductivity (EC) level of the substrate (Choi et al., 2013a, b). Commonly, irrigation schedules were based on monitoring soil-moisture status (Fares and Polyakov, 2006; Papadopoulos et al., 2008; Thompson et al., 2007) and required irrigation timing (Warren and Bilderback, 2004). The timing of irrigation, irrigation quantity per irrigation cycle, and the duration of each cycle for hydroponics have been determined using a variety of techniques, including a sensor of cumulative solar radiation and a time clock (Lizarraga et al., 2003; Lee et al., 2007). Unlike the time-clock method, irrigation by solar radiation applies more water when the crop needs more (Lizarraga et al., 2003); however, the authors postulated that during the morning hours from 10 a.m. until 12 p.m., when solar radiation is low, it takes more than 1 hour to reach the required radiation level (225 W m^{-2}), but during the middle hours, the irrigation interval is shorter than 30 minutes. In contrast, the automated FDR sensor appears to match the irrigation in the morning to the amount of water lost since the end of irrigation the previous day (Choi et al., 2013a, b). These results support that irrigation volume should be based on the amount of water lost since the last irrigation (Yeager et al., 1997).

In the present study, daily irrigation volume and water use efficiency (WUE) was affected by chip content in both commercial and two-story slabs (Table 2, Fig. 2). Consequently, the plant growth, fruit weight, and fruit numbers were significantly affected by the percentages of chip and dust in the slabs (Tables 3, 4). The highest plant growth, marketable fruit weights per plant, and WUE were observed in the commercial coir slab with 0% chips and 100% dust. In general, WUE varies with species and environmental factors (Burnett, 2008). The environmental factor in the present study is the substrate's physical property. In a FDR sensor-dependent automated irrigation for non-drainage system, frequency of irrigations is determined by crop demand, and most of portion of applied nutrient solution retains in substrate. At the beginning of cultivation, substrates have no soluble ions as washed off by water prior to transplanting, but with time, the substrate accumulates mineral nutrients. The accumulation processes occur depends on uptake rate by plant root, irrigation volume as well as the EC concentration in nutrient solution. In the present study, the substrate EC concentration ranged between 1.5 and 4.8 dS m^{-1} that started increasing from 30 DAT and decreasing from 75 DAT (Fig. 1C, D). The commercial slab with 30% chips and 70% dust and the rockwool slab had slightly higher EC concentration. While the EC level in the slab with 30% chips and 70% dust started increasing from about 55 DAT, the rockwool slab EC started greatly increasing from 30 DAT. These results indicate that an increase in the EC level in the slab with 30% chips and 70% dust may be related with the highest total irrigation volume (Table 2), which may have been demanded by their plant roots, producing relatively higher marketable fruits (Table 3). However, the long-term higher EC level in the rockwool slab may be associated with 100% retention of the applied nutrient solution without active root absorption since the plants grown the rockwool slab produced lower marketable fruits. The EC of the retained nutrient solution in the rockwool slab may have been adversely influenced root uptake of water and nutrient solution. All the integrated data indicate that the FDR sensor-automated irrigation may be more useful for tomato cultivation in coir substrate containing 0% chips and 100% dust using water efficiently and minimizing or avoiding leachate and thus reducing pollution. Detailed experiment would be necessary to closely focus on determining appropriate irrigation volume at each of irrigation as well as duration of each individual irrigation cycle depending on different physical properties of substrates using an automated irrigation system operated by the FDR sensor.

Acknowledgement

This study was supported by the Korea Institute of Planning and Evaluation for Technology in Food, Agriculture, Forestry and Fisheries (IPET).

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토마토 수경재배에서 FDR(Frequency Domain Reflectometry) 센서를 활용한 무배액 시스템에 적합한 코이어 배지의 Chip과 Dust 비율 구명

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적 요. 본 연구는 토마토 수경재배에서 Frequency Domain Reflectometry(FDR) 센서를 활용한 무배액 시스템에 적합한 코이어 배지의 chip과 dust 비율을 구명하기 위한 기초 실험으로 chip 함량에 따른 일일 급액량, 배액량, 배지의 용적당 수분함량 및 전기전도도, 식물생육, 과실 수량과 수분이용효율 측정을 목적으로 수행되었다. 시판 코이어 슬라브 중 chip과 dust 부피비율이 0 : 100%, 30 : 70%, 50 : 50%, 70 : 30%인 것과 대조구로 시판 rockwool 배지와 2층 슬라브, 즉 1층에 chip함량과 2층에 dust함량이 15 : 85%, 25 : 75%, 35 : 65%인 것을 사용하여 실험하였다. 실험에 사용된 배지 중 0 : 100%와 rockwool 배지는 전 생육기간 동안 배액이 배출되지 않았고 나머지 모든 배지에서도 극소량의 배액이 배출되었다. 일일 평균 급액량은 시판 슬라브와 2층 슬라브 배지 모두에서 chip 함량에 따라 다르게 나타났다. 식물 생육, 상품과 수량 및 수분이용효율은 chip과 dust의 비율이 0 : 100%인 시판 슬라브에서 가장 높게 나타났다. 따라서, FDR센서에 의한 자동급액 방식으로 토마토 작물을 재배 할 때 chip과 dust 부피비율이 0 : 100%인 코이어 배지를 사용할 경우 식물이 더욱 효과적으로 수분을 이용하여 생산량이 증가되면서도 배액을 최소화하거나 배액을 창출하지 않아 환경오염을 감소시킬 수 있다. FDR 센서에 의해 자동 급액되는 시스템에서 1회 급액량과 급액간격 기능을 생육단계별로 조정하여 배지의 물리성에 따른 급액 일정에 대한 세밀한 실험이 앞으로 수행될 계획이다.

추가 주제어 : 배액량, 이층배지, 용적 당 수분함량, 수분이용효율