Assessment of Water Control Model for Tomato and Paprika in the Greenhouse Using the Penman-Monteith Model

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Abstract. This paper investigated actual crop evapotranspiration (ET_c) of tomato and paprika planted in test beds of the greenhouse. Crop water requirement (CWR) is the amount of water required to compensate ET_c loss from the crop. The main objectives of the study are to assess whether the actual crop watering (ACW) was adequate CWR of tomato and paprika and which amount of ACW should be irrigated to each crop. ET_c was estimated using the Penman-Monteith model (P-M) for each crop. ACW was calculated from the difference of amount of nutrient supply water and amount of nutrient drainage water. ACW and CWR of each crop were determined, compared and assessed. Results indicated CWR-tomato was around 100 to 1,200 ml/day, while CWR-paprika ranged from 100 to 500 ml/day. Comparison of ACW and CWR of each crop found that the difference of ACW and CWR are fluctuated following day of planting (DAP). However, the differences could divide into two phases, first the amount of ACWs of each crop are less than CWR in the initial phase (60 DAP) around 500 ml/day and 91 ml/day, respectively. Then, ACWs of each crop are greater than the CWR after 60 DAP until the end of cultivation approximately 400 ml/day in tomato and 178 ml/day in paprika. ET_c assessment is necessary to correctly quantify crop irrigation water needs and it is an accurate short-term estimation of CWR in greenhouse for optimal irrigation scheduling. Thus, reducing ACW of tomato and paprika in the greenhouse is a recommendation. The amount of ACW of tomato should be applied from 100 to 1,200 ml/day and paprika is 100 to 500 ml/day depend on DAP.

Additional key words : actual crop watering, crop evapotranspiration, crop water requirement, greenhouse, watering

Introduction

Greenhouse is being considered as useful and widely adopted cultivation system that provides and maintains a controlled environment suitable for better crop growth (Chopda et al., 2018). To control the environmental factors in greenhouse is a complex task, the use of agricultural Internet of Thing (IoT) to monitor the factors within the system is an advanced option, to improve of quality and quantity of crop production with less utilization of water, fertilizer and pesticide especially irrigation scheduling to reduce wasted water and improve water use efficiency by monitoring crop water requirement (CWR) which depends mainly on evapotranspiration, ET (Perera et al., 2015).

ET is the combination of two separate processes whereby water is lost from the soil surface by evaporation and from the crop by transpiration. Evaporation and transpiration occur simultaneously and there is no easy way of distinguishing between the two processes (Allen et al., 1998). In greenhouse, transpiration is the main process to release the water that absorbed by crops to the atmosphere (Bakker et al., 1995). Thus, ET in greenhouse is dominated by transpiration from the plant while the evaporation value is very small due to very small or no open area exists (Fazlil llahi, 2009; Pamungkas et al. 2013). In addition, a conceptual approach to estimate crop-ET (ET_c) is using reference

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evapotranspiration (ET_o) and a crop coefficient (K_c), where ET_o is ET_c from the reference surface and K_c is the ratio between actual ET_c and ET_o (Perera et al., 2015). In another word, the amount of water required to compensate ET_c loss from the cropped is defined CWR. As a reason, ET_c assessment is necessary to correctly quantify crop irrigation water needs, playing a crucial role in greenhouse and water balance calculations (Choi et al., 2018: Nikolaou et al. 2019).

The most reliable and accurate method to determine ET_c is Lysimeters. The difficult, expensive and longtime requirement of the lysimeter method plays an important constraint in the preference of the equations based on climate to determine ET_c (Perera et al., 2015). There are various methods available to determine the rate of ET_c in greenhouses. These methods calculate for the total amount of water lost through transpiration and evaporation which depends on specific interactions among soil, crops and atmospheric conditions (solar radiation, air temperature, humidity and wind speed) in a greenhouse (Fazlil llahi, 2009). A main condition of the protected system is utilizing the plastic cover on the greenhouse. The plastic significant changes the internal radiation balance and the external environmental conditions, especially absorption and reflection of incident solar radiation (Fernandez et al., 2010).

There was no standard method in order to determine ET_c for greenhouse crops. However, the model which was the worldwide most widely used and accepted as a standard for determining crop water requirement was FAO adaptation of the Penman-Monteith equation: P-M (Costa, Poças and Cunha, 2019). For example, Sharma et al. (2017), using P-M equation to compute ET_a for drip-irrigated for three water treatments in chili pepper greenhouse: (1) control where water was applied near the surface using two drip emitters, (2) partial root zone drying vertical (PRDv) where subsurface irrigation was applied at 20 cm depth from soil surface, and (3) partial root zone drying compartment (PRDc). The result showed there was no significant difference of ET_a in three treatments. Moazed, Ghaemi and Rafiee (2014) reported the results of 13 different common daily ET_o estimation methods, namely FAO56 P-M, Hargreaves-Samanı, FAO-24 Blaney-Criddle, FAO-24 Radiation, Priestley-Taylor, Makkink, Turc, Linacre, Jensen-Haise, Copais, Pan Evaporation, R_n-radiation and R_s-radiation were compared with lysimetric

measurements in a plastic greenhouse to provide helpful information for selecting the appropriate ET_o equation to use. The results indicate that the FAO P-M methods was the most accurate methods for estimating daily ET_o in greenhouse conditions. Whereas, the least appropriate method was Linacre. For outdoor conditions, the best and worst results were obtained from FAO24-Radiation and Copias methods, respectively. Next, Alagha and Sangodoyin, 2013 applied P-M model estimating the irrigation water scheduling for tomato. Tomato cultivation was grown on six different soilless media inside a greenhouse in Nigeria. Villarreal-guerrero et al. (2012) compared three ET_o models (Stanghellini, P-M and Takakura) for pepper and tomato in the greenhouse. The results showed there were no statistically significant differences among ET_o predictions of the three models. Baptista et al. (2005) compared measured ET_o using a lysimeter and estimated ET_o model using P-M model for tomato crop in a Mediterranean greenhouse. The result presented that estimated ET_o values was similar with the measured ET_o indicating that the experimental data and model performance agree reasonably well. Moreover, Rahil and Qanadillo (2015) examined four irrigation regimes as follows: farmer irrigation (FI), tensiometer based irrigation (TI), irrigation at full ET_c data (ET_c), and irrigation at 70% of ET_c (70% ET_c). The results that the 70% ET_c treatment obtained the highest crop yield of 59.52 t ha^{-1}, while the yield for ET_c, FI, and TI treatments were 57.27, 55.81 and 45.10 t ha^{-1}, respectively. There was no significant difference in yield between FI, ET_c and 70% ET_c treatments. While the yield obtained under TI treatment was significantly less than the other treatments. On average, cucumber yield under 70% ET_c treatment was 24%, 6% and 4% higher than that under TI, FI and ET_c treatments, respectively. At the end of harvesting stage plant height, above-ground dry matter obtained by 70% ET_c treatment was higher than the other treatments. Moreover, several researches utilized crop models as essential tool in order to improve productivity, farm management, and yield and growth prediction (Karaca, et al. 2017; Woo, et al., 2000; Papadakis et al, 1994; Yang et al., 1989). Harmato et al. (2005) calculated ET_c based on PM method. Four different levels irrigation: 100, 75, 50 and 25% of ET_c were irrigated to tomato. To examine levels of irrigation that affect tomato growth and

yield within a poly-net greenhouse in Thailand. Two modes of irrigation application namely continuous and intermittent were used. The experiment showed that drip irrigation at 75% of ET_c provided the maximum crop yields and irrigation water productivity.

However, basic obstacle to widely applying the P-M formula requires knowledge of the numerous variables that are not easily available and lack of some variables in many areas (Moazed et al, 2014; Katsoulas and Stanghellini, 2019). To complete the formula, more sensors need to implement to measure microclimatic parameters i.e. air temperature, relative humidity, wind speed, global solar radiation, soil temperature as well as specific crop parameter such as the aerodynamic, stomata conductance and leaf temperature. As a result, the most irrigation of greenhouse crops is mainly controlled on the basis of solar radiation due to unavailability of sensing devices and cost consideration (Harman et al., 2005: Sharma et al., 2017). Furthermore, sensors are defined as any instrument, using sensors to collect some types of physical or chemical characteristic and converts that measurement into a signal. It can be read by an observer or automated data collection system. Thus, it is important to understand the different limitations of sensors that affect measurements. Lastly, three qualifications of sensor to be considered: accuracy, precision and resolution to be implement for a particular purpose (van Iersel, Chappell and Lea-cox. 2013).

The main objectives of the study were 1) to assess whether ACW was adequate CWR of tomato and paprika in greenhouse and 2) how much amount of water should be managed for tomato and paprika in the future cultivation.

Materials and Methods

In this study, the cultivation of tomato (*Solanum lycopersicum* cv. dafnis) was cultivated twice, the first cropping was conducted in November 2017 to May 2018 and the second cultivation was in August 2018 to May 2019 and three paprika varieties (*Capsicum annuum* cv. sirocco, volante and orandino). Paprika was cultivated during September 2018 to May 2019. The crops were carried out in the greenhouse of the Division of Smart Farm Development located at National Institute of Agricultural Sciences (35°48¢N latitude, 127°44¢E longitude and 37 m altitude). The greenhouse has a dimension of 7 m x 75 m x 4 m (W x L x H) covered with 1.0 mm polyethylene vinyl as cladding material. All climatic data outside and inside the greenhouse were automatically collected by sensors. For the outside greenhouse conditions, air temperature and humidity were measured every 5 minutes using a sensor (WJ-TH0101, Naretrend (Xspark), Bucheon-si, Korea). Precipitation data was measured every 5 minutes using a sensor (DRC3000, Woosung Tech, Yangsan-si, Korea). Wind speed was measured every 5 minutes using a sensor (Davis7911, Davis, USA). Inside the greenhouse, air temperature was measured by a sensor (NTC 10K, Naretrend (Xspark), Bucheon-si,
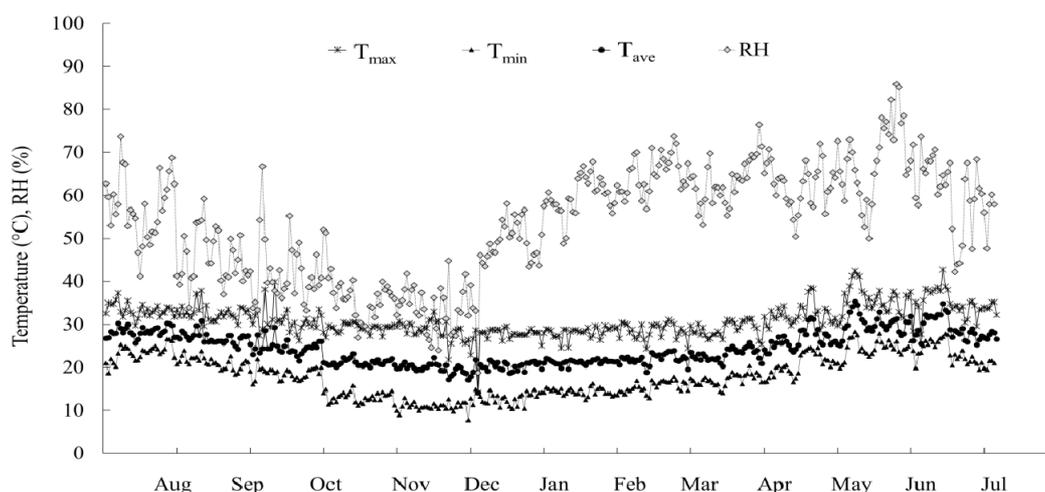

Fig. 1. Climatic conditions of the greenhouse.

Siriluk Somnuek, Youngsin Hong, Minyoung Kim, Sanggyu Lee, Jeonghyun Baek, Kangsu Kwak, Hyondong Lee, and Jaesu Lee

Korea) in every 5 minutes and humidity was measured placed 2 m above the plants using a sensor (FS-220H, Naretrend (Xspark), Bucheon-si, Korea) in every 5 minutes. The averaged data from January 2017 to May 2019 are stored in the Cloud-database system (Baek et al., 2018). The air temperature of the greenhouse has a maximum range of 15ºC to 43ºC and minimum range from 8ºC to 28ºC. RH ranged 20% to 90% (Fig. 1).

Weather data from 2017-2019 were used to calculate the daily reference evapotranspiration (ET$_o$) by P-M equation (FAO, 2005) defined by equation (1) below:

$$ET_o = \frac{0.408 \triangle (R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\triangle + \gamma (1 + 0.34 u_2)} \tag{1}$$

where: ET_o is reference evapotranspiration (mm/day), Rn is net radiation at the crop surface (MJ/m^2/day), G is soil heat flux density (MJ/m^2/day), T is the mean daily air temperature at 2 m height (°C), u_2 is wind speed at 2 m height (m/s), e_s is saturation vapor pressure (kPa), e_a is actual vapor pressure (kPa), e_s - e_a is saturation vapor pressure deficit (kPa), D is slope vapor pressure curve (kP/ °C), g is psychrometric constant (kPa/°C).

In this study, daily T$_{max}$, T$_{min}$ and T$_{ave}$. were computed ET using the P-M equation (1) which was calculated into an Excel Spreadsheet. R_n was calculated follow as the equations of Allen et al. (1998). After calculating ET$_o$, the reference evapotranspiration of the grass will be adjusted by the crop specific K$_c$ factor. K$_c$ is called the crop coefficient to the crop evapotranspiration, ET$_c$:

$$ET_c = ET_o * K_c \tag{2}$$

where: ET_c is crop evapotranspiration (mm/day), ET_o is reference evapotranspiration (mm/day), and K_c is crop coefficient, K_c of tomato and paprika is 1.15 and 1.05 (Allen et al., 1998).

Next, CWR is the amount of water in milliliter (ml) that should be irrigated to each crop inside the greenhouse derived from ET$_c$ (millimeter, mm/day). The conversion from mm to ml followed Tan (1990). ACW was calculated from the difference of amount of nutrient supply water and

amount of nutrient drainage water. In addition, nutrition solution that irrigated to tomato was EC values ranged 2.5 to 2.8, pH was 5.5 to 6.5 and defoliation was keeping leave around 11 to 14. For paprika, EC was 2.5 to 3.0, pH was 5.5 to 6.5. While, keeping leave of paprika as possible. Finally, the theoretical model of CWR and ACW were compared and assessed. However, this study was the estimation of ET$_c$ or CWR, it will not be actual CWR of each crop in this greenhouse, the estimation could be a guideline of the water control model of each crop for the next cultivation.

Results

1. Tomato cultivation in the greenhouse
1.1. ET$_o$ and ET$_c$ of tomato

Temperature inside the greenhouse are higher than outside temperature throughout the season while average relative humidity outside is higher than inside of the structure (data not shown). Tomato cultivation in the greenhouse started in August to May. ET$_o$ for inside greenhouse were calculated using climatic data. ET$_o$ (cross dots) ranges at 0.5 mm/day to 7 mm/day. The highest estimation of ET$_o$ was from June to August at 6 mm/day to 7 mm/day while ET$_o$ was the lowest from November to February at 0.5 mm/day to 2 mm/day. ET$_c$ of tomato is multiplying ET$_o$ and K$_c$ tomato is 1.15 (Fig. 2).

1.2 ET$_c$ and CWR in developmental stages of first tomato cultivation

This study has experimented twice cultivations for tomato. The first tomato cultivation was conducted on November 1, 2017 to May 31, 2018 (213 days). ET$_c$ of first tomato cropping is shown in Fig. 2. ET$_c$ of the initial stage (November) is around 1 mm/day. ET$_c$ decreases to reach the lowest values around 0.5 mm/day in December (30-40 Days of planting, DAP) and ET$_c$ increases to 6 mm/ day in May. CWR is the amount of water that should be irrigated to tomato. CWR ranges from 100 ml/day to 300 ml/day (90 DAP) and increases from 300 ml/day to 1,300 ml/day until 210 DAP (Fig.3).

The comparison of ACW (round dots) and CWR (cross dots) in different stages is shown in Fig.3. The graph illustrates that ACW is fluctuated. There are days of ACW
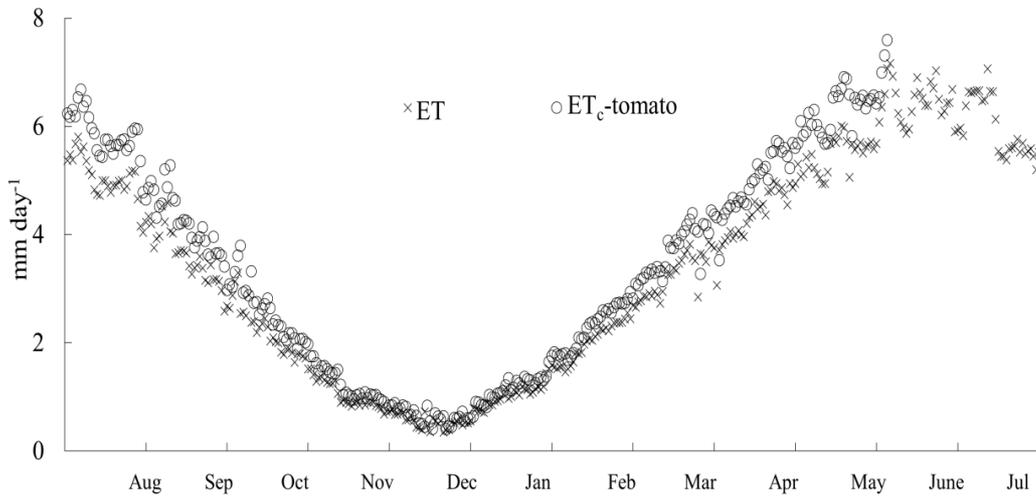
Fig. 2. Daily reference evapotranspiration (ET) and crop evapotranspiration of tomato ET_c from August to July under greenhouse conditions.
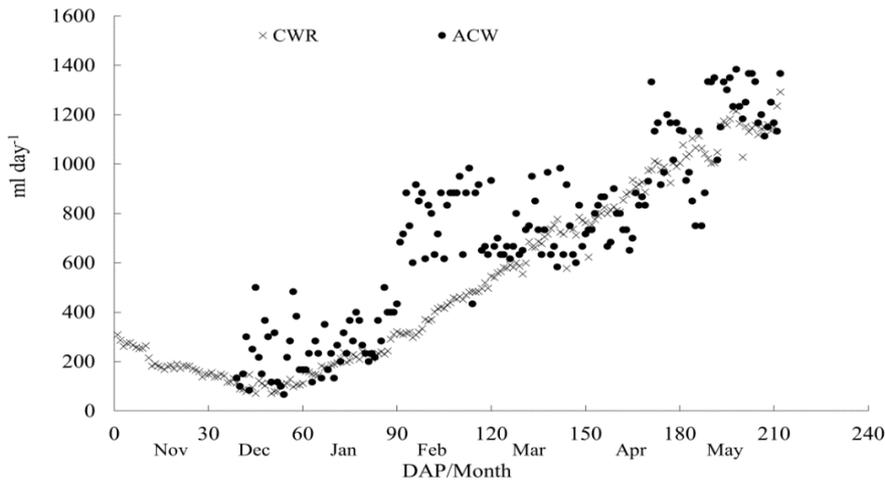

Fig. 3. Comparison of estimated crop water requirement (CWR) and actual crop watering (ACW) of the first tomato cultivation.

are greater than estimated CWR from 117 ml/day to 983 ml/day or 21% to 84%. The average of excess water is approximately 570 ml/ day or 45%, from 40 DAP to 130 DAP. While, there are days of actual crop watering are less than CWR from 67 ml/day to 1,133 ml/day or 17% to 95%. The average of less water is around 650 ml/ day or 32% after 130 DAP.

1.3 ET_c and CWR in developmental stages of the second tomato cultivation

The second cultivation was August 1, 2018 to May 12, 2019 (286 days). As shown in Fig. 2, ET_c in August started from 5 mm/day and declined to mm/day in December. ET_c

continuously increased to 5 mm/day in May. In Fig. 4, during the initial stage, the crop would need water at around 1,200 ml/day. November to January (90 DAP to 150 DAP), CWR is about 100 mm/day to 200 ml/da[1]. Then, CWR increases from 300 ml/day to 1,200 ml/day (until 286 DAP). ACW was calculated as the 1st tomato cultivation, from September 30, 2018 to May 31, 2019. In Fig. 4, the comparison of CWR and ACW. At the beginning of the cultivation (53 DAP), ACW is less than CWR from 91 ml/day to 764 ml/day or 16% to 300%. The average of the less water is around 335 ml or 80%. From 54 DAP to 190 Day, the graph illustrates that ACW is greater than CWR from 73 ml to 480 ml or 22% to 81%. The average of the excess water is around 236 ml/day
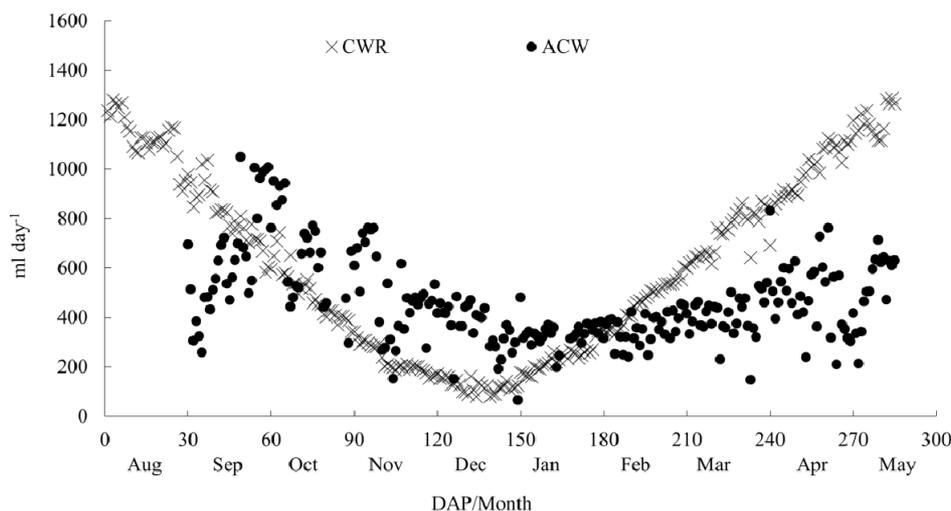
Fig. 4. Comparison of crop water requirement (CWR) and actual crop watering (ACW) for the second tomato cultivation.

or 50%. After 190 DAP until 286 DAP, ACW is less than CWR from 78 ml/day to 944 ml/day or 21% to 443%. The average of the less water is around 402 ml/day or 103%.

2. Paprika cultivation in the greenhouse

2.1. ET_o and ET_c of paprika

ET_o for inside greenhouse were calculated using climatic data. ET_o (cross dots) ranges at 0.5 mm/day to 7 mm/day. ET_c of paprika by multiplying ET_o with K_c-paprika is 1.05. The paprika cultivation started in September 2018 to May 2019 (273 days). ET_c of paprika is around 4 mm/day in the initial cultivation (September). ET_c decreases to 1 mm/day during November to January then increases to 5 mm/day in April to May (Fig. 5).

2.2 ET_c and CWR in developmental stages of the paprika cultivation

CWR of Paprika is around 100 ml/day to 400 ml/day during September to January. CWR from January to May ranges from 100 ml/day to 500 ml/day. The comparison of CWR and ACW found that at the beginning to 57 DAP, ACW is applied to paprika lower than CWR around 25 ml/day to 200 ml/day or 15% to 460%. The average of less water is 91 ml/day or 150%. After that most of ACW is greater than CWR applied until harvesting around 35 ml/day to 466 ml/day or 15% or 83%. The average of excess water is 178 ml/day or 50% (Fig. 6).

Discussion

From the results ET_c of the crops were high due to high temperature of the summer period (September). Later on, ET_c started to decline from October to December from 5 mm/day to 0.5 mm/day. During the final phase, ET_c increased until reaching high values in May from 0.5 to 7 mm/day. Jayasekara et al. (2018) mentioned the relationship between greenhouse type, greenhouse cover, greenhouse climate, ventilation conditions in the greenhouse, and plant should be examined in detail in greenhouse conditions because these changes are directly related to ET_c. Harmanto et al. (2005) explained that ET_c for tomato in the tropical country is fluctated according to the microclimate on the respective day and crop development stages. The irrigation of crops will depend on daily climatic data from inside greenhouse directly. Aiswarya et al. (2019) reported ET_c value for green chilli inside a greenhouse was found to be less when compared to the open field for all the cultivation due to the less demand for evaporation. However, ET_c in the greenhouse and outside in the last period were high due to the full growth period of chilli. Kitta et al. (2014) calculated ET_o of sweet pepper in different screenhouses using the P-M model. The screenhouses differed by their shading factors (SF), defined as the complement of the solar radiation transmittance. The result showed different values of ET_c in the screenhouse had changed following in the different shading factors in August and September. As a reason, ET_c
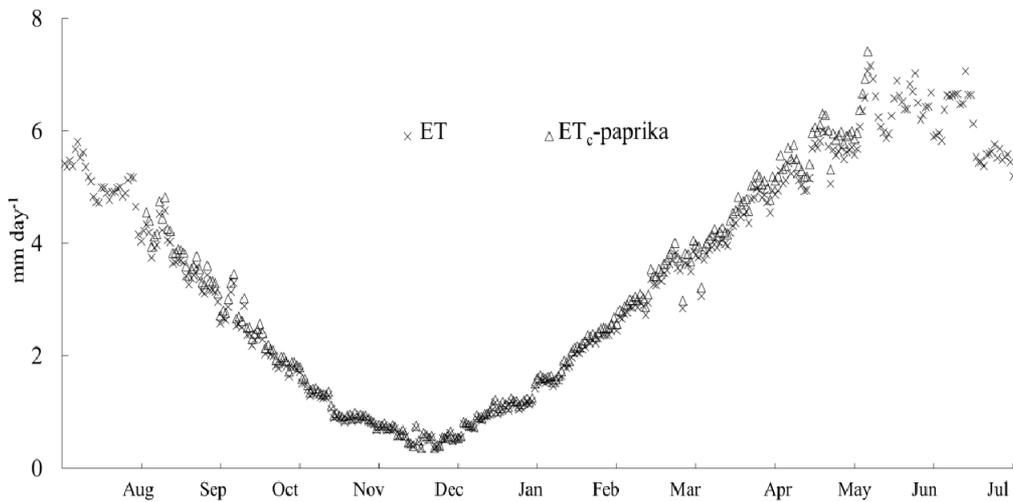
Fig. 5. ET$_o$ and ETc- paprika from August to July under the greenhouse conditions.
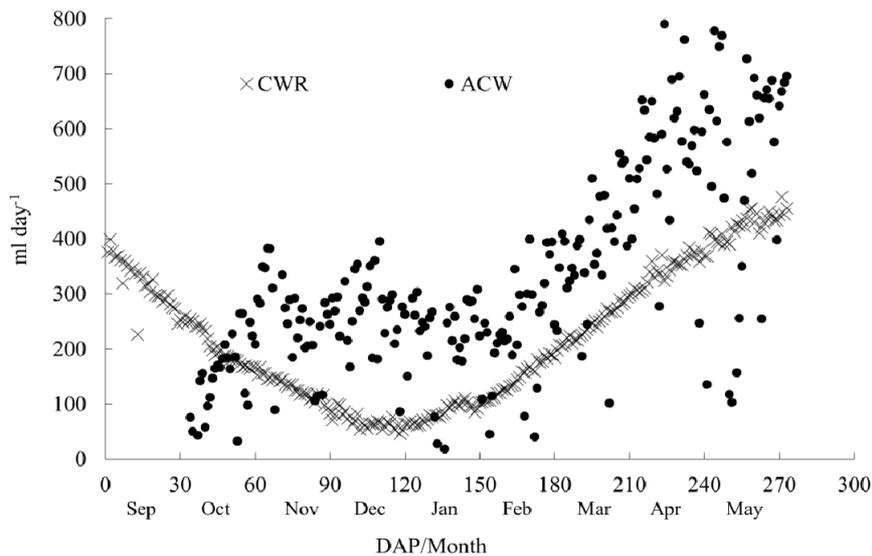

Fig. 6. Comparison of estimated crop water requirement (CWR) and actual crop watering (ACW) for paprika.

can be influenced by climatic data, DAP, cultivated timing and farming management and types and materials of greenhouses.

In Fig. 3, 4 and 6, in the initial phase, tomato and paprika received ACW and were less than CWR. However, the crop still grew well (data not shown) because even there were insufficient water irrigation, the levels of water shortage of the crops have not reached the permanent wilting point and the irrigation scheduling in the greenhouse was applied every day. The days that received excess water could compensate the days receives less water. As Snyder (1992) reported an important point is that plants should receive

enough water that they do not wilt, if plants reach the "permanent wilting point," tissue is permanently damaged and they will not recover, even with plenty of water. Moreover, in Fig. 3 and 4 found CWR is high at the beginning of the planting, however, in the initial planting as the tomato seedling is still small, it needs less water as Snyder (1992) recommended that newly transplanted plants only need about 50 ml/plant/day. Harmanto et al. (2005) reported tomato (Troy 489 variety) in tropical zone was applied water 100, 75, 50 and 25% of ET$_c$, based on PM model, were tested for their effect on crop growth and crop yield. The results showed that tomato was applied water as

Siriluk Somnuek, Youngsin Hong, Minyoung Kim, Sanggyu Lee, Jeonghyun Baek, Kangsu Kwak, Hyondong Lee, and Jaesu Lee

75% of ET_c or 4.1 to 5.6 mm/day or 300 to 400 ml/plant/day had a high LAI value 4.8, the highest height was 1.5 m after 75 days planting and the highest yields was 0.44 kg m^{-2} compared with other treatments.

In addition, this study measured ACW for tomato and paprika as the difference between the amount of nutrient supply water and the amount of drained water. We found some days percentage of the drained water was higher than 20% of both crops as Snyder (1992) mentioned in case of tomato the drainage in the greenhouse should be around 10% to 20%. Thus, reducing ACW for tomato and paprika is recommended in term of saving water. Furthermore, Lizarraga et al. (2003) mentioned that water and fertilizers can be saved, greenhouse systems are not profitable because disinfection of irrigation is expensive. Moreover, some days the crops received ACW than CWR because the irrigation in the greenhouse is measured by the substrate moisture content. When it is less than 20% ACW increase to maintain a range of the moisture of substrate around 20% to 30%. As we mentioned above that there were researchers about ET_c in greenhouse using the P-M model to monitor CWR. In contrast, the commercial irrigation in the greenhouse is mainly controlled on the basis of solar radiation as PRIVA system from the Netherlands as implementing in Korean farmers' greenhouse. The farmers applied this system due to after service of the company and more convenience (field visiting). Nikolaou et al. (2019) stated the level irrigation will depend on either the greenhouse microclimate or on substrate moisture status and irrigation scheduling bases on direct or indirect measurement of plant water status and plant physiology that respond to water deficit. Pérez-Castro et al. (2017) suggested that the substrate moisture content and ET_c from climatic data and the constructed decision condition for irrigation scheduling on tomatoes grown directly in soil and soilless systems will be a suitable management in the greenhouse.

Conclusion

We assessed the water control model of tomato and paprika cultivation in the greenhouse using the P-M model to estimate ET_c of each crop which as defines as CWR. ACW was calculated from the difference of amount of

nutrient supply water and amount of nutrient drainage water. Then, comparisons of ACW and CWR of each crop to assess whether ACW could compensate CWR or not. The comparison of ACW and CWR in each crop shows that ACW of tomato and paprika are less than CWR in the initial phase (60 DAP) around 500 ml/day and 91 ml/day, respectively. However, ACWs of each crop is greater than CWR after 60 DAP until the end of cultivation around 400 ml/day and 178 ml/day. It means ACW can compensate CWR but the amounts of ACW were excessive especially in paprika. As ET_c is the optimal method to quantify the amount of irrigation in greenhouse. Thus, reducing ACW will be a recommendation for each crop. The suggestion of ACW for tomato is 100 to 1,200 ml/day and paprika is 100 to 500 ml/day.

To improve the existing irrigation system in terms of water use efficiency and having more precision of ET_c in the greenhouse, measurement of ET_c directly is needed with the use of class A pan setup is recommended. However, the estimated ET_c is ET_o x K_c, for this study, K_c values were applied from Allen et al. (1998). Albuquerque et al. (2012) for bell pepper crop in Recife, PE, Brazil, and Lozano et al. (2017) for the melon crop in Maringá, PR, Brazil, differed from those suggested in the literature. This further study that K_c must be adjusted for each region. In addition, monitoring volumetric water content using dielectric sensors e.g., time domain reflectometry, frequency domain is suggested. However, ET_c was converted to CWR for comparison with ACW. CWR could be overestimated due to the use of fixed maximum value of plant growth for the estimation especially in the initial phase of planting as the seedling is small. As a result, CWR should be less. For future research, applying simulation programs to investigate CWR in real time is needed.

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Literature Cited

Aiswarya, L., K. Arunadevi, R. Lalitha, and S. Vallalkannan. 2019. Estimation of actual crop evapotranspiration of green chili in semi-arid region under different atmospheric condition. International journal of current microbiology and applied sciences 8:1104-1110. https://doi.org/10.20546/ijcmas.2019.805.127

Albuquerque, F.S., E.F.F. Silva, J.A.C. Albuquerque Filho, and G.S. Lima. 2012. Water requirement and crop coefficient of fertigated sweet pepper. Brazilian journal of Irrigation and drainage 17:481-493.

Allen, R. G., L. S. Pereira, D. Raes, and M. Smith. 1998. Crop evaporation–guidelines for computing crop water requirements. FAO Irrigation and drainage paper 56. FAO.

Baek, J. H., J. W. Heo, H. H. Kim, Y. Hong, and J. S. Lee. 2018. Research platform design for the Korea smart greenhouse based on cloud computing. Protected horticulture and plant factory 27:27-33.

Bakker, J. C., G. P. A. Bot, H. Challa, and N. J. van de Braak. 1995. Greenhouse Climate Control. Wageningen Pers, Wageningen, The Netherlands. 15-160.

Baptista, F. J., B. J. Bailey, and J. Meneses. 2005. Measuring and modelling transpiration versus evapotranspiration of a tomato crop grown on soil in a Mediterranean greenhouse. Acta horticulture 691:313-320.

Choi, Y., M. Y. Kim, S. O'Shaughnessy, J. G. Jeon, Y. J. Kim, and W. J. Song. 2018. Comparison of artificial neural network and empirical models to determine daily reference evapotranspiration. Journal of the Korean society of agricultural engineer 60: 43-54. https://doi.org/10.5389/KSAE.201860.6.043

Chopda, A., A. P. Sahu, D. M. Das, B. Panigrahi, and S. C. Senapati. 2018. Variation in actual evapotranspiration of green chili inside and outside the rooftop greenhouse under deficit irrigation. International journal of current microbiology and applied sciences 7:4152-4159.

Costa, P. M., I. Poças, and M. Cunha 2019. Modelling evapotranspiration of soilless cut roses "Red Naomi" based on climatic and crop predictors. Horticultural science 46:107-114. https://doi.org/10.17221/147/2017-HORTSCI

Fazlil llahi, W. F. 2009. Evapotranspiration models in greenhouse. Master's Thesis, Wageningen University.

Fernandez, M. D., S. S. Bonachela, F. Orgaz, R. Thompson, J. C. Lopez, M. R. Granados, M. Gallardo, and E. Fereres. 2010. Measurement and estimation of plastic greenhouse reference evapotranspiration in a Mediterranean climate. Irrigation science 28:497-509.

Harmanto, V., M. Salokhe, M. S. Babel, and H. J. Tantau. 2005. Water requirement of drip irrigated tomatoes grown in greenhouse in tropical environment. Agricultural water management 71:225–242.

Jayasekara, S. N., W. H. Na, A. B. Owababi, J. W. Lee, A. Rasheed, H. K. Kim, and H. W. Lee. 2018. Comparison of environmental conditions and insulation effect between air inflated and conventional double layer greenhouse. Protected horticulture and plant factory 27:46-53.

Karaca C., B. Tekelioğlu, D. Büyüktaş, and R. Baştuğ. 2017. Assessment of the equations computing reference crop evapotranspiration. Academia journal of engineering and applied sciences ICAE-IWC (Special Issue):144-161.

Katsoulas, N. and C. Stanghellini. 2019. Modelling crop transpiration in greenhouses: Different models for different applications. Agronomy 9:1-17. https://doi.org/10.3390/agronomy9070392

Kitta, E., A. Baille, N. Katsoulas, and N. Rigakis. 2014. Predicting reference evapotranspiration for screenhouse-grown crops. Agricultural water management 143:122-130. https://doi.org/10.1016/j.agwat.2014.07.006

Lozano, C. S., R. Rezende, P. S. L. Freitas, T. L. Hachmann, F. A. S. Santos, and A. F. B. A. Andrean. 2017. Estimation of evapotranspiration and crop coefficient of melon cultivated in protected environment. Revista brasileira de engenharia agrícola e ambiental 21:758-762.

Lizarraga, A., H. Boesveld, F. Huibers, and C. Robles. 2003. Evaluating irrigation scheduling of hydroponic tomato in Navarra, Spain. Irrigation and drainage 52:177-188.

Moazed, H., A. A. Ghaemi, and Rafiee, M. R. 2014. Evaluation of several reference evapotranspiration methods: a comparative study of greenhouse and outdoor condition. Iranian Journal of Science and Technology. Transactions of civil engineering 38:421-437.

Nikolaou, G., D. Neocleous, N. Katsoulas, and C. Kittas. 2019. Review: irrigation of greenhouse crops. Horticulture 5:1-20.

Pamungkas, A. P., K. Hatou, and T. Morimoto. 2013. Modeling the evapotranspiration inside the greenhouse systems by using matlab simulink. In IFAC Proceedings Volumes 46: 33-37. Retrieved from https://doi.org/10.3182/20130327-3-JP-3017.00010

Papadakis, G., A. Frangoudakis, and S. Kyritsis. 1994. Experimental investigation and modelling of heat and mass transfer between a tomato crop and greenhouse environment. Journal of Agriculture engineering research 57:217-227.

Perera, K. C., A. W. Western, B. Nawarathna, and B. George. 2015. Comparison of hourly and daily reference crop evapotranspiration equations across seasons and climate zones in Australia. Agricultural water management 148: 84-96. https://doi.org/10.1016/j.agwat.2014.09.016

Siriluk Somnuek, Youngsin Hong, Minyoung Kim, Sanggyu Lee, Jeonghyun Baek, Kangsu Kwak, Hyondong Lee, and Jaesu Lee

Pérez-Castro, A., J. A. Sánchez-Molina, M. Castilla, and J. Sánchez-Moreno. 2017. cFertigUAL: A fertigation management app for greenhouse vegetable crops. Agricultural water management 183:186-193.

Rahil, M. H. and A. Qanadillo. 2015. Effects of different irrigation regimes on yield and water use efficiency of cucumber crop. Agricultural water management 148:10-15.

Snyder, R. G. 1992. Greenhouse tomato handbook. Publication No. 1828. Mississippi State University. Cooperative extension service, USA. p. 30.

Sharma, H., M. K. Shukla, P. W.Bosland, and R. Steiner. 2017. Soil moisture sensor calibration, actual evapotranspiration, and crop coefficients for drip irrigated greenhouse chile peppers. Agricultural water management 179:81-91. https://doi.org/10.1016/j.agwat.2016.07.001

Tan, C. S. 1990. Irrigation scheduling for fruit crop: low- volume drip or micro-sprinkler systems. Ministry of Agriculture, Food and Rural Affairs of Canada. Accessed 15 July, 2019. Retrieved from http://www.omafra.gov.on.ca/ english/crops/facts/90-069.htm#b.

van Iersel, M. W., M. Chappell, and J. D. Lea-cox. 2013. Sensors for improved efficiency of irrigation in greenhouse and nursery production. American society for horticultural science 23:735-746.

Villarreal-Guerrero, F., M. Kacira, E. Fitz-Rodríguez, C. Kubota, G. A. Giacomelli, R. Linker, and A. Arbel. 2012. Comparison of three evapotranspiration models for a greenhouse cooling strategy with natural ventilation and variable high-pressure fogging. Scientia Horticulture 134: 210-221.

Woo, Y. H., H. J. Kim, Y. I. Nam, I. H. Cho, and Y. S. Kwon. 2000. Predicting and measuring transpiration based on phyto monitoring of tomato in greenhouse. Protected horticulture and plant factory 41:459-463.

Yang, X., T. H. Short, R. D. Fox, and W. L. Bauerle. 1989. The Microclimate and transpiration of a greenhouse cucumber crop. American society of agricultural engineers 32:2143-2150.

Penman-Monteith을 이용한 토마토와 파프리카의 증발산 모델 평가

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적 요. ET_c 손실을 보상하는데 필요한 물의 양을 작물 용수 요구량(Crop water requirement, CWR)로 정의되며, ET_c 평가는 작물 필요 요구량을 정확하게 정량화하는 데 필요하며, 물 균형 계산에서 중요한 역할을 한다. 토마토와 파프리카의 실제 관수 요구량(Actual crop water, ACW)이 적절한 CWR인지 평가하였다. 토마토와 파프리카 재배에 적정한 AWC 예측 및 추정을 위하여 온실 내부 환경데이터를 Penman-Monteith을 이용하여 기준 작물 증발산(ET)을 계산한 후, 기준 증발산은 작물 상수(Kc;토마토-1.15, 파프리카-1.05)계수로 조정하였다. 토마토와 파프리카의 CWR과 ACW를 계산하여 비교 평가한 결과 ACW가 CWR을 대체할 수 있지만 파프리카의 ACW는 필요 이상으로 높게 나타났다. 또한, 토마토의 ACW는 1일 100 ~ 1,200 ml이고, 파프리카의 ACW는 1일 100 ~ 500 ml가 적절한 것으로 나타났다. 그러나, 스마트 온실에서 ET_c의 정밀도를 높이려면, ET_c가 CWR로 변환되고 ACW와 비교하기 위해서 클래스 A팬 설정이 필요하다. 향후 실시간으로 CWR을 측정하기 위한 시뮬레이션 프로그램 연구가 필요하다.

추가 주제어: 기준 작물 증발산, 관개, 관수 요구량, 온실