Evaluation of Several Reference Evapotranspiration Models and Determination of Crop Water Requirement for Tomato in a Solar Greenhouse

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Additional index words. drip irrigation, dual crop coefficient, plant transpiration, soil evaporation, solar greenhouse

Abstract. Studies on dual crop coefficient method in a greenhouse require accurate values of reference evapotranspiration (ET_0). This study was conducted in a solar greenhouse at the experimental station of the Chinese Academy of Agricultural Sciences during 2015 and 2016. An automatic weather station was installed in the center of the same greenhouse to record weather parameters at 30-minute intervals. Five ET_0 models (Penman-Monteith, Penman, radiation, pan evaporation, and Priestley-Taylor) were employed, and their performance was evaluated using the dual crop coefficient method. The basal crop coefficient K_{cb} and soil evaporation coefficient K_e were adjusted according to the surrounding climate inside the greenhouse. Crop evapotranspiration (ET_c) was continuously measured using sap flow system combined with microlysimeter in 2015 and weighing lysimeters in 2016. Daily ET_0 was simulated from the five models and compared with the measurements. Results show that the adjusted K_{cb} values were 0.15, 0.94, and 0.65 in 2015 and 0.15, 1.02, and 0.70 in 2016 at initial, midseason, and late-season, respectively. The K_e varies between 0.10 and 0.45 during the whole growth period. The ET_c was ≈ 345 mm for drip-irrigated tomato in solar greenhouse at the whole growth stage. The radiation and pan evaporation models tend to overestimate ET_0 values. Results of the Penman-Monteith, Penman, and Priestley-Taylor models show comparatively good performance in estimating ET_0 . Considering the robustness and simplicity, the Priestley-Taylor was recommended as the first choice to estimate ET_0 of tomato grown in a solar greenhouse. This work can help farmers to optimize the irrigation scheduling based on an ET_0 model for solar greenhouse vegetables in northern China.

A solar greenhouse is an energy-saving greenhouse that consists of gables on both sides, a maintenance rear wall, a supporting skeleton, and covering materials. It is different from glass and plastic greenhouse in two

ways. First, there is no heating system in a solar greenhouse. The heat in the daytime comes from solar radiation and in the evening comes from the rear wall and surface soil. Second, the top and south vents are used to

regulate temperature and humidity according to the characteristics of crop growth. These simple-structured greenhouses have emerged as a favorite technique in northern China because it bridges the season gap in vegetable and fruit production (Wei and Sun, 2014). Tomato (*Lycopersicon esculentum*) has high nutritional value, rich in vitamins A, B₁, B₂, and C in carotene and calcium (Lupini et al., 2017). In recent years, greenhouse tomato cultivation has been becoming an important industry for the local economy. A large amount of water is needed to supply tomatoes cultivated in a greenhouse, especially in the flowering and fruit setting stages (Gong et al., 2017a). Deep groundwater has been extracted for irrigation to maintain tomato production. Long-term overexploitation of groundwater resources will lead to a series of environmental degradations (e.g., soil salinization and desertification) (Xia et al., 2016). Therefore, improving water use efficiency is an effective way to maintain long-term greenhouse development.

ET_c is an important parameter for determining a scientific and rational irrigation schedule to improve water use efficiency (Qiu et al., 2017, 2019; Yan et al., 2017; Yuan et al., 2001). Establishing an ET_c model is a simple method to get water requirements of crops, thus many greenhouse ET_c models have been developed. For example, the FAO56 Penman-Monteith (PM) model is the most commonly used because of its simple structure and relatively high precision (Allen et al., 1998). However, its application was still limited due to less information on two forms of resistance (e.g., aerodynamic resistance and canopy resistance). The structure of PM model must be redefined if applied in a greenhouse. Aerodynamic resistance has usually been considered a function of wind velocity, but it can become infinite when wind velocity is close to zero. Zhang and Lemeur (1992) reported that the aerodynamic resistance can be calculated by using the heat transfer coefficient inside greenhouse, but this coefficient needs canopy temperature, which is difficult to obtain. Because the PM model was insensitive to the aerodynamic resistance, several studies treat it as a constant in different greenhouse types (Fernández et al., 2010, 2011; Gong et al., 2017b; Yan et al., 2018). For surface resistance, it is usually estimated using the ratio of stomatal resistance to the effective leaf area index (Allen et al., 1998). Gong et al. (2017b) developed a bulk surface resistance model by combining the restrictions of soil and canopy to water vapor transfer for estimating the tomato ET_c in solar greenhouse. Yan et al. (2018) indicated that the establishment of the canopy resistance model was related to days after transplant and net radiation. However, there are arguments about whether these resistance models can be appropriated for the whole growth stages in a solar greenhouse.

The dual crop coefficient method has also been used widely to determine crop water requirements, especially in solar greenhouse (Gong et al., 2017c; Qiu et al., 2015). This method consists of three parts: the basal crop

coefficient (K_{cb}), soil evaporation coefficient (K_e), and reference ET_o . In most cases, the K_{cb} and K_e need to be adjusted according to surrounding environmental and crop factors (Allen et al., 1998, 2005). For example, Ding et al. (2013a) developed an improved dual crop coefficient method for better predicting crop transpiration through K_{cb} and soil evaporation through K_e . Qiu et al. (2013) investigated effect of planting density on the K_{cb} by introducing a density coefficient. The adjusted K_{cb} and K_e were also used to estimate the greenhouse tomato ET_c , and obtained the K_{cb} values at the initial, midseason, and late-season stages (Gong et al., 2017c). In addition, Rosa et al. (2012a, 2012b) developed a SIMDualKc software based on dual crop coefficient method and applied it to make irrigation scheduling for rainfed and basin irrigated maize and furrow irrigated cotton. The SIMDualKc model was also calibrated and validated for estimating hot pepper ET_c in a solar greenhouse (Qiu et al., 2015). We have more research on the crop coefficient, however, fewer studies focus on the ET_o , resulting in limitation of the dual crop coefficient method in a solar greenhouse. It is thus necessary to evaluate several models for estimating greenhouse ET_o . Doorenbos and Pruitt (1977) proposed four methods to calculate ET_o in the FAO Irrigation and Drainage Paper No. 24 (FAO24), including the FAO24 Penman, radiation, pan evaporation, and Hargreaves models. Fernández et al. (2010) indicated that the Hargreaves and the radiation methods were recommended to calculate ET_o in the plastic greenhouse due to simplicity and precision. However, these models are validated only in the Mediterranean climatic regions. Considering the differences of climatic region and greenhouse characteristics, the ET_c simulation of solar greenhouse with natural ventilation cannot be well presented by current research results. Therefore, whether these models can be applied to semihumid continental climate in northern China remains to be validated. In addition, as a simplification of the Penman equation, the Priestley-Taylor model (Priestley and Taylor, 1972), was often used to calculate greenhouse ET_o . In this model, the ET_c process was governed by net radiation, air temperature, and pressure for a surface that extends over a large surface area. Accuracy of the Priestley-Taylor model mainly

Table 1. Textural and basic soil hydraulic properties of the greenhouse experimental site.

Soil layer (m)	Clay (%)	Silt (%)	Sand (%)	θ_{Fc} ($m^3 \cdot m^{-3}$)	θ_{WP} ($m^3 \cdot m^{-3}$)
0.0–0.2	20.6	79.4	0	0.30	0.09
0.2–0.4	21.4	78.6	0	0.32	0.09
0.4–0.6	20.8	78.0	1.2	0.31	0.08
0.6–0.8	11.2	78.1	10.7	0.34	0.10
0.8–1.0	10.4	69.3	20.3	0.33	0.10

θ_{Fc} and θ_{WP} represent the soil water content at field capacity and the wilting point, respectively.

Table 2. Tomato planted at the study site and its length of growing stage.

Yr	Start date	End date	Growing stage (d)				Total d
			Initial	Development	Mid	Late	
2015	10 Mar.	15 July	31	33	37	27	128
2016	9 Mar.	12 July	32	32	36	27	127

depends on parameter α , which is a function of environmental factors (such as leaf area index and solar radiation) (Sumner and Jacobs, 2005). Ding et al. (2013b) indicated that the α was a function of leaf area index, vapor pressure deficit, and soil moisture content. Many studies have shown that taking α as 1.26 can be applied to many vegetated areas (Valdés-Gómez et al., 2009; Szilagyi, 2014; Tongwane et al., 2017). However, how to determine the value of α in a solar greenhouse has not been defined yet.

As stated earlier, the purpose of this work was to determine the best model for estimating ET_o in a solar greenhouse by comparing the PM, Penman, radiation, pan evaporation, and Priestley-Taylor models. The authors hope to apply it for greenhouses to develop an irrigation scheduling.

Materials and Methods

Experimental site and design

Site description. The experiment was conducted at the experimental station of the Xinxiang Comprehensive Experimental Base of the Chinese Academy of Agricultural Sciences, located in the northern of Henan Province, China (lat. 35°09' N, long. 113°5' E, altitude 78.7 m). The experimental site was located in a warm temperate continental monsoon climate zone with a mean annual temperature of 14.5 °C. The materials of the solar greenhouse included a steel frame and covering with plastic film (0.2-mm-thick nondrop polyethylene sheet). The length and width of the solar greenhouse was 60 and 8.5 m, respectively, it was oriented east–west, without heating equipment and passively ventilated by opening the plastic film on the top and the south. The experimental soil of 0.0 to 1.0 m was silt loam, with a mean bulk density of 1.49 g·cm⁻³, wilting point water content, and field soil water capacity of 0.09 and 0.32 cm³·cm⁻³, respectively. The main characteristics are presented in Table 1.

The greenhouse was uniformly planted with tomato crops (Mill. cv. Jingding). The plot was 8.8 m² (8.0 m long × 1.1 m wide) with 50 plants planted in two rows. There were 18 plots in total, and the planting density was

Table 3. Standard (initial) and calibrated basal crop coefficients, p depletion fractions, and soil evaporation parameters for the greenhouse tomato.

	Standard (Initial)	Calibrated
$K_{cb\ ini}$	0.15	0.15, 0.15 a
$K_{cb\ mid}$	1.10	0.94, 1.02 a
$K_{cb\ end}$	0.70	0.65, 0.70 ^z
p_{ini}	0.40	0.50
p_{dev}	0.40	0.50
p_{mid}	0.40	0.50
p_{end}	0.40	0.50
REW (mm)	9	8
TEW (mm)	20	22
Z_e (m)	0.10	0.10

^zFrom Allen et al. (1998, 2005).

5.7 plants/m². Tomato seedlings were transplanted on 10 Mar. 2015 and 9 Mar. 2016 and irrigated with a drip irrigation system (the distance between emitters was 30 cm, and flow rate was 1.1 L·h⁻¹). The irrigation amount and frequency were determined on the basis of the accumulated water evaporation of the D20 pan placed above the canopy. Irrigation events were conducted when the cumulative pan evaporation reached 20 ± 2 mm. Twenty millimeters of water were applied by drip irrigation after transplanting to ensure the survival of seedlings. Fifteen times of irrigation were performed, and the amount of water was 282.4 and 280.7 mm in 2015 and 2016, respectively. The length of initial, development, midseason, and late-season stages are shown in Table 2. Similar agronomic management, such as fertilization, pollination, and pest control, was conducted throughout the study period.

Sample collection and analyses

Meteorological factors and pan evaporation. An automatic weather station was installed in the center of the same greenhouse. Solar radiation (R_s), net radiation (R_n), air temperature (T_a), relative humidity (RH), and air speed (u) at 2.0 m aboveground level were constantly monitored. These sensors were radiometer (LI200X; Campbell Scientific Inc., Logan, UT), net radiometer (NR LITE2; Kipp and Zonen BV, Delft, The Netherlands), temperature and humidity recorder (CS215), and air velocity meter (Gill

Received for publication 30 Aug. 2019. Accepted for publication 23 Oct. 2019.

Published online 17 January 2020.

Supported by the National Natural Science Foundation of China (51809094, 51579102, and 51709110) and Key Technologies R & D and the Program of Henan Province (192102110090). We thank the editors and anonymous reviewers for their constructive input during the review phase of the paper.

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WindSonic, Lymington, UK), respectively. In addition, the soil heat flux (G) was measured using heat flux plates (HFP01; Hukseflux, Delft, The Netherlands) at 5 cm below the ground surface. All data were collected with a CR-1000 data logger (Campbell Scientific Inc.) every 10 s, and 30-min averages were calculated.

A D20 pan is used to measure the pan evaporation at 30 cm above the canopy surface. The rain gauge with an accuracy of 0.1 mm was used to measure pan evaporation at 8:00 AM every day, and 20 mm of water was added after each measurement to ensure water quality.

Soil evaporation. Soil evaporation within two rows was continuously measured from March to July in 2015 and 2016 using micro-lysimeters, which was made from galvanized iron. It consisted of an inner and outer cylinder, 10 and 12 cm diameter, respectively, and 15 cm height. To reduce measurement errors and ensure easy operation without destroying the soil structure, the following operations were performed: 1) the outer cylinder was embedded in the soil beforehand, keeping the top edge level with the soil surface; 2) the inner cylinder was pushed inside the soil and the base sealed with plastic foil after it was removed; 3) inner cylinder mass was weighed using an electronic balance with a precision of 0.1 g every day at 8:00 AM; 4) inner soil was replaced at 2-d intervals and after irrigation; and 5) six repetitions were conducted.

Plant transpiration. Sap flow system (Flow 32-1k system; Dynamax, Houston, TX) was used to measure plant transpiration continuously from 15 May to 15 July 2015 and 14 Apr. to 10 July 2016. To ensure the rationality of measurement and reduce errors, the following processing were conducted: 1) eight healthy plants consistent in leaf area index were randomly selected; 2) sap flow meters were fixed at 20 cm above ground to avoid the effect of soil radiation on probes; 3) the specifications were required to meet the requirements of the tomato stem diameter to ensure close contact between the probes and the stem; 4) in the first stage, plant transpiration was obtained by minus soil evaporation from crop ET_c , which was measured by water balance approach in 2015 and weighing lysimeter in 2016. The plant transpiration data were collected every 15 min by a CR-1000 data logger (Campbell Scientific Inc.).

Evapotranspiration. The ET_c was measured from March to July 2016 using two weighing lysimeters (1.0 m long, 1.0 m wide, and 1.2 m deep), which were located in the same greenhouse. To obtain more accurate measurements, the following procedures were followed: 1) soil texture in the weighing lysimeter was the same as in the field; 2) six seedlings were randomly selected, and the planting pattern was the same as outside; and 3) plants were supported with bamboo poles to avoid interference from outside crops.

Soil moisture content and growth indexes. Five ECH₂O sensors (5TE; Decagon De-

Fig. 1. Variations of (A) solar radiation (R_s), (B) water vapor pressure deficit (VPD), (C) air temperature (T_a), and (D) pan evaporation (E_{pan}) during 2015 and 2016 in the study's solar greenhouse.

vices, Inc., Pullman, WA) were used to continuously monitor volumetric soil moisture content, which were installed in the middle of two drippers on the same drip tape. The measured depths were 10, 20, 30, 40, and 60 cm respectively. All data were collected every 30 min using an EM50 data logger (Decagon Devices, Inc.). Three repetitions

were conducted to improve measurement accuracy in each plot.

Growth indexes included tomato height, leaf area index, and root length. Thirty plants were sampled at the center to measure height and leaf area index at 7-d intervals. Detailed measurement methods can be found in Gong et al. (2017b). Root length was measured

using a root auger at the initial, development, midseason, and late-season stages. Roots were removed every 10 cm until no roots were found. Two repetitions were conducted because of the heavy workload.

Models and parameters

Five reference ET_o models were evaluated and compared in this work, including the FAO56 PM, FAO24 Penman, FAO24 radiation, FAO24 pan evaporation, and Priestley-Taylor models.

PM model. In this model, the aerodynamic resistance was set to $308 \text{ s}\cdot\text{m}^{-1}$ based on the research conclusion of Gong et al. (2017b). Then the expression was as follows (Monteith, 1965):

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma[608VPD/(T_a + 273)]}{\Delta + 1.23\gamma} \quad [1],$$

where ET_o is the crop reference evapotranspiration ($\text{mm}\cdot\text{d}^{-1}$); R_n is the net radiation ($\text{MJ}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$); G is the soil heat flux ($\text{MJ}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$); Δ is the slope of the saturation water vapor pressure vs. temperature curve ($\text{kPa}\cdot^\circ\text{C}^{-1}$); γ is the psychrometric constant ($\text{kPa}\cdot^\circ\text{C}^{-1}$); T_a is the air temperature ($^\circ\text{C}$); and VPD is the water vapor pressure deficit (kPa).

FAO 24 Penman model. This model can be expressed as follows (Doorenbos and Pruitt, 1977):

$$ET_o = c \left[0.408R_n \left(\frac{\Delta}{\Delta + \gamma} \right) + 2.7VPD \right] \left(1 + 0.01U_2 \left(\frac{\gamma}{\Delta + \gamma} \right) \right) \quad [2],$$

where c is the adjustment factor, which is affected by solar radiation, relative humidity and air speed. Other symbols have the same meaning as in Eq. [1].

FAO 24 radiation model. This model can be expressed as follows (Doorenbos and Pruitt, 1977):

$$ET_o = b \times R_s \left(\frac{\Delta}{\Delta + \gamma} \right) - 0.3 \quad [3],$$

where b is the adjustment factor, which is affected by relative humidity and air speed, and R_s is the daily solar radiation ($\text{mm}\cdot\text{d}^{-1}$). Other symbols have the same meaning as in Eq. [1].

FAO 24 pan evaporation model. This model can be expressed as follows (Doorenbos and Pruitt, 1977):

$$ET_o = K_p \times E_{pan} \quad [4],$$

where K_p is the pan coefficient, which is affected by solar radiation, relative humidity, air temperature, and wind speed, and E_{pan} is the daily pan evaporation ($\text{mm}\cdot\text{d}^{-1}$).

Priestley-Taylor model. This model can be expressed as follows (Priestley and Taylor, 1972):

$$ET_o = \alpha \frac{\Delta}{\Delta + \gamma} (R_n - G) \quad [5],$$

where α is the Priestley-Taylor constant that generally needs to be corrected according to the surrounding climate.

Fig. 2. Variations of the basal crop coefficients (K_{cb}), soil evaporation coefficient (K_e) and standard K_{cb} for greenhouse tomato in 2015 (A) and 2016 (B).

Fig. 3. Dynamics of tomato evapotranspiration in solar greenhouse during the whole growth period in 2015 and 2016.

Other symbols have the same meaning as in Eq. [1].

Dual crop coefficients method. In this method, the effects of soil evaporation and plant transpiration are determined separately and divide crop coefficient into a basal crop coefficient (K_{cb}) and soil evaporation coefficient (K_e). The approaches for the calculation of ET_c are implemented as follows:

$$ET_c = (K_{cb} + K_e) \cdot ET_o \quad [6],$$

where ET_c is the crop evapotranspiration ($\text{mm}\cdot\text{d}^{-1}$). A complete computation process of the K_{cb} and K_e are presented in the papers by Allen et al. (2005) and Rosa et al. (2012a).

When calculating K_e , the soil field capacity and soil wilting point between 0 and 15 cm were measured to be $0.31 \text{ m}^3\cdot\text{m}^{-3}$ and $0.10 \text{ m}^3\cdot\text{m}^{-3}$. Other parameters, such as root-zone soil field capacity, root-zone soil wilting point, maximum root depth, average fraction of soil surface wetted by irrigation, and leaf senescence factor are $0.32 \text{ m}^3\cdot\text{m}^{-3}$, $0.09 \text{ m}^3\cdot\text{m}^{-3}$, 1.0 m, 0.35, and 0.2, respectively. Standard (initial) and calibrated K_{cb} at initial, midseason, and late-season stages, p depletion fractions, and soil evaporation parameters for the greenhouse tomato are presented in Table 3.

Performance indicators

The performance indicators include coefficient of determination (R^2), mean absolute

error (MAE), root mean square error (RMSE), and index of agreement (d_i), defined as follows:

$$R^2 = \frac{\left[\sum_{i=1}^N (Q_i - \bar{Q})(P_i - \bar{P}) \right]^2}{\left[\sum_{i=1}^N (Q_i - \bar{Q})^2 \sum_{i=1}^N (P_i - \bar{P})^2 \right]} \quad [7],$$

$$MAE = \sum_{i=1}^N |Q_i - P_i| / N \quad [8],$$

$$RMSE = \left[\sum_{i=1}^N (Q_i - P_i)^2 / N \right]^{0.5} \quad [9],$$

$$d_i = 1 - \frac{\sum_{i=1}^N (Q_i - P_i)^2}{\sum_{i=1}^N (|P_i - \bar{Q}| + |Q_i - \bar{Q}|)^2} \quad [10],$$

where Q_i and P_i are the measured and simulated data, respectively; $\bar{Q}$ and $\bar{P}$ is the mean of the measurements and simulations; and N is the number of measurements. The perfect model will have $R^2 \approx d_i \approx 1.0$ and $MAE \approx RMSE \approx 0$. The best model should approach the preceding limits.

Results and Discussion

Variations of meteorological factors in greenhouse. To reveal the variations of meteorological factors inside the solar greenhouse, solar radiation (R_s), water vapor pressure deficit (VPD), air temperature (T_a), and pan evaporation (E_{pan}) were investigated primarily in 2015 and 2016.

Figure 1A shows that the daily R_s changed from 0.74 to 19.97 MJ·(m²·d⁻¹) with an average of 11.73 and 11.02 MJ·(m²·d⁻¹) in 2015 and 2016, respectively. The maximum and minimum R_s occurred in July and March, respectively. Daily VPD varied from 0.02 to 2.46 kPa with a mean of 0.74 kPa for the 2 study years (Fig. 1B). In contrast to R_s , VPD did not present a clear variation trend. However, T_a shows a similar trend with R_s , which often reached the peak value in July. Daily T_a changed from 10.87 to 31.75 °C with a mean of 22.90 °C for the 2 study years (Fig. 1C). The variation trend was the closest between R_s and E_{pan} . It is noteworthy that the maximum daily E_{pan} was 7.8 mm and the minimum was only 0.12 mm for the entire period (Fig. 1D). Many studies found that E_{pan} was close to ET_c . For example, McVicar et al. (2007) stated that monthly ET_c can be represented by E_{pan} . Zuo et al. (2016) indicated that there was a complementary relationship between E_{pan} and ET_c . Bian et al. (2016) reported that the correlation coefficients between the monthly ET_c and E_{pan} was 0.894, and an empirical evapotranspiration model based on the relationships between monthly ET_c and the leaf area index, precipitation, and E_{pan} was established.

Crop coefficient curves. Following the proposed segment approach in the FAO56 manual, the tomato growing phase was divided into four stages: initial, development, midseason, and late-season. The initial and midseason stages were characterized by horizontal line segments, whereas the development and late-season were characterized by rising and falling line segments, respectively. Figure 2 shows the variations of the basal crop coefficient, K_{cb} , and soil evaporation coefficient, K_e , which was adjusted according to the greenhouse environment in 2015 and 2016. Results show that the change trend was similar between adjusted K_{cb} and the standard K_{cb} , but there were small differences at the midseason and late-season stages. Detailed descriptions are as follows: at the initial stage, $K_{cb\,ini}$ was not adjusted and reached a value of 0.15 based on the FAO56 manual. At midseason and late-season stages, $K_{cb\,mid}$ and $K_{cb\,end}$ had to be adjusted due to environmental differences inside the greenhouse (RH_{min} was not equal to 45%, u_2 was not equal to 2 m·s⁻¹). Meanwhile, $K_{cb\,mid}$ and $K_{cb\,end}$ were greater than 0.45. Thus, the values of adjusted $K_{cb\,mid}$ and $K_{cb\,end}$ were 0.94 and 0.65 in 2015 and 1.02 and 0.70 in 2016, respectively. $K_{cb\,mid}$ was lower than the standard value (1.10), whereas $K_{cb\,end}$ was between the standard value (0.6 to 0.8). Many studies have shown that the adjusted $K_{cb\,mid}$ was often lower than the standard $K_{cb\,mid}$

Fig. 4. Comparison between daily values of estimated vs. measured evapotranspiration (ET_o) in solar greenhouse. ET_o values were estimated by FAO56 Penman-Monteith (A), FAO24 Penman (B), FAO24 radiation (C), FAO24 pan evaporation (D), and Priestley-Taylor (E). Each point corresponds with a daily ET_o value from 2015 to 2016.

recommended by FAO56 manual. Similar studies can also be found in Qiu et al. (2015) and Gong et al. (2017c). The possible reasons for $K_{cb\,mid}$ lower than the standard $K_{cb\,mid}$ are the following: 1) higher humidity and lower air transfer in the solar greenhouse can result in lower K_{cb} values (Allen et al., 1998); and 2) the walkway was set at ≈ 30 cm, resulting in reduction of total plant transpiration, which lowered the K_{cb} (Qiu et al., 2013).

K_e was affected by topsoil moisture content and canopy coverage rate primarily (Rosa et al., 2012a). In the initial stage, because of the small LAI and large exposed surface area, K_e was between 0.11 and 0.41 in 2015 and between 0.07 and 0.43 in 2016. In the development stage, K_e changed from 0.02

to 0.35. With the increasing of canopy coverage ratio, K_e decreased gradually but increased after irrigation. At the midseason and late-season stages, K_e was between 0.07 and 0.19 in both study years. Normally, the higher topsoil moisture content, the larger value of the K_e (Gong et al., 2017c). Rosa et al. (2012b) also indicated that K_e was high when the topsoil was wet after irrigation and the canopy was small.

Evaluation of five reference evapotranspiration models. Variations of tomato ET_c during the entire growth period are presented in Fig. 3. Results show that daily ET_c was smaller at the initial stage and increased gradually at the late-season stage. Daily ET_c changed from 0.12 to 6.66 mm·d⁻¹ with a mean of 2.82 mm·d⁻¹ in 2015 and from 0.32

to 6.65 mm·d⁻¹ with a mean of 3.01 mm·d⁻¹ in 2016. The average daily ET_c was 1.65 and 1.15 mm·d⁻¹, 2.53 and 2.70 mm·d⁻¹, 3.98 and 3.52 mm·d⁻¹, 3.42 and 3.86 mm·d⁻¹ at initial, development, midseason, and late-season stages in 2015 and 2016, respectively. With the increase of R_s and T_a , the water requirement of crops increases gradually. Niu et al. (2011) indicated that daily ET_c of greenhouse cucumber was largest at full fruit stage under drip irrigation, and the amount of ET_c at this stage accounts for 69.6% of total ET_c. Wang et al. (2009) also indicated that the maximum daily ET_c occurs at the peak fruit stage, when total ET_c changes from 60.9 to 100.42 mm. Similar results were validated in greenhouse melon (Sensoy et al., 2007) and pepper (Qiu et al., 2013). The reasons for this phenomenon can be described as follows: high radiation with air temperature, and low humidity will lead to the increase of leaf transpiration rate and crop water requirement. In this case, crop roots need to constantly absorb water from the soil to meet the water demand of fruit expansion (Gong et al., 2017a; Qiu et al., 2013).

The parameters b , c , K_p , and α from the radiation, Penman, pan evaporation, and Priestley-Taylor models were determined through simultaneous measurements of ET_c and (*Lycopersicon esculentum*) coefficient using the inversing method. Here, the ratio of ET_c to ($K_{cb}+K_e$) was the measured ET_o. Comparison of daily crop ET_o between the estimated and measured values in the solar greenhouse are presented in Fig. 4. Results show that five models can better estimate daily ET_o, most estimated data are closely distributed around the 1:1 line. The performance of five models are as follows:

The PM model was recommended as the standard method for calculating field crop ET_o (Allen et al., 1998). However, it underestimated greenhouse tomato ET_o by 10.1% over 2 study years, with the slopes of regression equation of 0.89, MAE of 0.45 mm·d⁻¹, RMSE of 0.58 mm·d⁻¹, and d_i of 0.95 (Table 4). Many meteorological factors of

the PM model should be measured, resulting in a decrease in precision. In addition, the parameter of aerodynamic resistance (r_a) in the PM model is a function of wind velocity, and it will reach infinity when wind velocity is close to zero. Some studies indicated that r_a oscillates between 100 and 500 s·m⁻¹ in greenhouse (Bailey et al., 1993; Fernández et al., 2010, 2011; Gong et al., 2017b; Katsoulas et al., 2001). Villarreal-Guerrero et al. (2012) indicated that adjustment of the parameters r_a and stomatal resistance limits the application of the PM model in a greenhouse under variable high-pressure fogging.

The Penman and Priestley-Taylor models were similar in estimating ET_o, and slightly overestimated ET_o by 8.3% and 6.7%, at two growth seasons with slopes of 1.08 and 1.06, MAE of 0.45 and 0.46 mm·d⁻¹, RMSE of 0.59 and 0.60 mm·d⁻¹ respectively. The correction parameter values of c for the Penman and α for the Priestley-Taylor methods were stable in the solar greenhouse with mean values of 1.10 and 0.55, respectively. Muniandy et al. (2016) indicated that the Penman model ($c = 0.35$) was found to be the best model for estimating daily ET_o of bittergourd and chili in the field. Fernández et al. (2010) indicated that taking c as 0.96 was more suitable in the whitened greenhouse. For the Priestley-Taylor model, net radiation (R_n) and α are two necessary parameters, where α also needs to be adjusted according to surrounding environment. Ding et al. (2013b) indicated that α was a function of leaf area index, vapor pressure deficit, and soil moisture content, and the value was different at each growth stage. For example, Valdés-Gómez et al. (2009) reported that the Priestley-Taylor model predicted greenhouse tomato ET_c with an error of 6.1% when the α value was 1.26. This parameter was often applied in the field crops (Szilagyi, 2014; Tongwane et al., 2017). Although the Priestley-Taylor model slightly overestimated the measured ET_o, considering its robustness and simplicity, this model was used as the

first choice to estimate crops ET_o in a solar greenhouse.

The performance of the radiation and pan evaporation models was slightly worse in estimating greenhouse ET_o; the correction parameter values of b for the radiation model and K_p for the pan evaporation model was 1.14 and 1.00, respectively. The radiation and pan evaporation models overestimated ET_o by 14.1% and 14.4% at two growth seasons, with regression coefficients of 1.14 and 1.16. The reason for the large deviation can be attributed to the effect of solar radiation on leaf stomata. Except for solar radiation, the VPD was also an important factor affecting ET_c that cannot be ignored in a greenhouse condition (Gong et al., 2017a). Bonachela et al. (2006) also indicated that solar radiation was the main environmental factor affecting greenhouse ET_c, followed by VPD. The restrictive conditions of water entering the atmosphere from plants are related to VPD, and the effect of meteorological factors on latent heat flux is largely realized by changing the VPD (Zhang et al., 2016).

Conclusions

Total evapotranspiration for greenhouse tomato with drip irrigation was ≈ 345 mm during the entire growth period. The amount of ET_c was the largest at the midseason stage, which accounted for 69.6% of total ET_c. The $K_{cb\ ini}$ was 0.15, and the adjusted $K_{cb\ mid}$ were lower than the standard (0.94 for 2015 and 1.02 for 2016). Adjusted $K_{cb\ end}$ was 0.65 and 0.70 in 2015 and 2016, respectively. K_e was mainly affected by surface coverage and soil moisture and varied between 0.10 and 0.45 throughout the growth period. Daily greenhouse tomato ET_o was estimated by the PM ($r_a = 308$ s·m⁻¹), Penman ($c = 1.1$), radiation ($b = 1.14$), pan evaporation ($K_p = 1.0$), and Priestley-Taylor ($\alpha = 0.55$) methods. The PM, Penman, and Priestley-Taylor were found to be a better methods than radiation and pan evaporation methods, although ET_o was slightly underestimated by PM and

Table 4. Summary of statistics from the comparison between predicted (P, mm·d⁻¹) and measured (Q, mm·d⁻¹) values of mean daily greenhouse ET_o.

ET _o method	Yr	Regression equation	R ²	N	P	Q	MAE	RMSE	d _i
FAO56 Penman-Monteith	2015	ET _{o-PM} = 0.89ET _{o-ME}	0.79	97	2.83	3.11	0.49	0.64	0.93
	2016	ET _{o-PM} = 0.89ET _{o-ME}	0.93	97	2.96	3.33	0.41	0.52	0.96
	Total	ET _{o-PM} = 0.89ET _{o-ME}	0.87	194	2.90	3.22	0.45	0.58	0.95
FAO24 Penman	2015	ET _{o-PE} = 1.08ET _{o-ME}	0.78	97	3.45	3.11	0.52	0.69	0.93
	2016	ET _{o-PE} = 1.07ET _{o-ME}	0.93	97	3.58	3.33	0.37	0.47	0.97
	Total	ET _{o-PE} = 1.08ET _{o-ME}	0.86	194	3.51	3.22	0.45	0.59	0.95
FAO24 radiation	2015	ET _{o-RA} = 1.21ET _{o-ME}	0.62	97	3.90	3.11	0.93	1.21	0.83
	2016	ET _{o-RA} = 1.08ET _{o-ME}	0.92	97	3.59	3.33	0.42	0.53	0.97
	Total	ET _{o-RA} = 1.14ET _{o-ME}	0.74	194	3.75	3.22	0.68	0.93	0.90
FAO24 pan evaporation	2015	ET _{o-PA} = 1.22ET _{o-ME}	0.66	97	3.89	3.11	0.94	1.27	0.83
	2016	ET _{o-PA} = 1.10ET _{o-ME}	0.92	97	3.63	3.33	0.45	0.60	0.96
	Total	ET _{o-PA} = 1.16ET _{o-ME}	0.77	194	3.76	3.22	0.69	0.99	0.89
Priestley-Taylor	2015	ET _{o-PT} = 1.05ET _{o-ME}	0.74	97	3.36	3.11	0.52	0.67	0.93
	2016	ET _{o-PT} = 1.06ET _{o-ME}	0.91	97	3.54	3.33	0.41	0.52	0.97
	Total	ET _{o-PT} = 1.06ET _{o-ME}	0.84	194	3.45	3.22	0.46	0.60	0.95

ET_{o-PM}, ET_{o-PE}, ET_{o-RA}, ET_{o-PA}, and ET_{o-PT} are the daily reference evapotranspiration estimated by Penman-Monteith, Penman, radiation, pan evaporation, and Priestley-Taylor methods, respectively. ET_{o-ME} is the daily reference evapotranspiration measured by the inversing method. R² is coefficient of determination, N is total number of observations, P is mean predicted values (mm·d⁻¹), Q is mean measured values (mm·d⁻¹), MAE is mean absolute error (mm·d⁻¹), RMSE is root mean square error (mm·d⁻¹), and d_i is index of agreement.

slightly overestimated by the radiation and pan evaporation methods. Because it required fewer parameters and less precision, the Priestley-Taylor method is recommended as the first choice to estimate crop ET_0 for solar greenhouse. This work can not only be applied to other solar greenhouses with similar weather conditions, but can also help farmers develop irrigation scheduling for greenhouse vegetables.

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