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Estimation of Greenhouse-Grown Eggplant Evapotranspiration Based on a Crop Coefficient Model

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Abstract: Accurate estimation of crop evapotranspiration (ET_c) is important to determine crop water requirements in greenhouse agriculture and to improve the irrigation water use efficiency. Here, a 3-year (2017–2019) experiment with spring greenhouse-grown eggplant (*Solanum melongena L.*) was conducted to investigate variation in the crop coefficient (K_c) measured with a weighing lysimeter, adjust K_c based on the local climate ($K_{c,Adj}$), and estimate daily ET_c using a crop coefficient model. The 3-years mean local K_c ($K_{c,Loc}$) were 0.23 ± 0.03, 0.62 ± 0.06, 1.05 ± 0.03 and 0.87 ± 0.03 at the initial, development, mid-season, and end-season stages, respectively. Significant linear correlation was observed between $K_{c,Adj}$ and $K_{c,Loc}$ in the 3 years (R^2 = 0.873, 0.901, and 0.897 in 2017–2019, respectively). Compared with the FAO-56 recommended K_c value ($K_{c,FAO}$), the mean $K_{c,Adj}$ and $K_{c,Loc}$ in the 3 years were by 66.3% and 61.8% lower, respectively. The single crop coefficient model accurately estimated daily ET_c for greenhouse-grown eggplant. The coefficient of determination (R^2), mean absolute error (MAE), root-mean-squared error (RMSE), and index of agreement between measured ET_c and that estimated by the single crop coefficient model were 0.94, 0.35 mm·d^{-1}, 0.26 mm·d^{-1}, and 0.98, respectively, for the means in 2018 and 2019. Therefore, the crop coefficient method reliably estimated evapotranspiration with adjustment for the actual environment and can serve as a useful tool to improve water use efficiency.

Keywords: greenhouse-grown eggplant; reference crop evapotranspiration; weighing lysimeter; daily evapotranspiration; crop coefficient

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1. Introduction

Globally, the production of vegetables in greenhouses has developed rapidly in recent years, due to its good economic benefits and being relatively unaffected by changes in the seasons. Eggplant (*Solanum melongena* L.) is among the most widely planted vegetables worldwide [1]. Global annual eggplant production is currently around 56.3 million tons, of which China alone produces 36.6 million tons [2]. Eggplant fruit contains a variety of alkaloids and high levels of anthocyanins, which are beneficial for human health, for example, in suppressing cancer and lowering blood lipids level, while also having a high level of chlorogenic acid [3,4]. Previous studies reported that a suitable irrigation schedule improves the yield and quality of eggplant fruit [5,6].

Crop evapotranspiration (ET_c) plays an important role in formulating a reasonable irrigation scheme and realizing effective water management of crops, and is crucial for the energy and water balance in agricultural ecosystems. Measurement of ET_c can be performed directly by experimental observations (e.g., using the eddy covariance method or a weighing lysimeter) or by estimation with a model (e.g., the crop coefficient method or Priestley–Taylor coefficient). The crop coefficient method is regarded as a reliable approach to estimate ET_c that multiplies reference evapotranspiration (ET_0) by a crop coefficient (K_c), as described in the 'FAO-56′ document by Allen et al. [7]. ET_0 is the rate of evapotranspiration with an assumed reference crop height of 0.12 m, fixed surface resistance of 70 s·m^{-1}, and albedo of 0.23, and its calculation has been standardized by the FAO-56 [7,8]. K_c represents the integration of the effects of the primary characteristics that distinguish the specific crop from the reference crop [7–9]. Recommendations on the lengths of four stages of crop development and corresponding typical K_c values for different crops are presented in FAO-56, and recently K_c has been updated for vegetable crops [10,11]. However, K_c values vary greatly at different stages of crop growth and are affected by crop characteristics, climate, cultivation, and management methods. Therefore, it is necessary to adjust the recommended K_c value based on local data sets when using the crop coefficient model to estimate ET_c. Wang et al. [12] reported that a modified crop coefficient model can provide a reliable prediction of daily ET_c. The estimated and observed ET_c showed a linear regression relationship during four maize growth seasons over four years, with coefficient of determination (R^2) values ranging from 0.80 to 0.88 and the root-mean-squared error (RMSE) ranging from 0.45 to 0.68 mm. Compared with the soil water balance method, the estimated ET_c at each maize development stage estimated with the crop coefficient method was less than 3.0%, but the error for the entire growth season was only 1.9% [13]. To date, although many studies have discussed and developed crop coefficients for grain crops (e.g., wheat and maize) and fruit tree crops (e.g., grapes and citrus), and some studies have attempted to investigate the daily K_c of greenhouse-grown eggplant based on the water balance method [14], the accuracy of the crop coefficient method for estimating ET_c for eggplant requires assessment.

The greenhouse cultivation environment is characterized by high temperature, high relative humidity, and poor air circulation. The method of calculating ET_0 in a greenhouse differs in terms of the value of aerodynamic resistance incorporated into the calculation from that in an open-air environment [15], and a K_c value from an open-air environment will result in a large error if applied to a greenhouse environment [16]. It is questionable whether the standard recommended K_c value that was determined experimentally outdoors can be applied directly to estimate the ET_c of greenhouse crops. In addition, the change in K_c at each crop development stage and its relationship with climate have not been considered, affecting the accuracy of ET_c estimation [10,12]. Therefore, it is important to revise the K_c value at different growth stages for greenhouse-grown eggplant and to study its dynamics. A weighing lysimeter is considered to provide the most accurate and reliable measurement of ET_c, and is considered the standard for the calibration of crop coefficients, as indicated in the FAO-56 methodology [17]. However, to the best of our knowledge, there is a lack of studies addressing this wider characterization of K_c for eggplant grown in greenhouses. Thus, the main objectives of the present study were to explore the dynamic variation in K_c of greenhouse-grown eggplant at different crop growth stages based on ET_c measurements with a lysimeter from 2017 to 2019, and to assess the performance of the crop coefficient method for estimating ET_c, to achieve precise moisture management for greenhouse-grown eggplant.

2. Materials and Methods

2.1. Experimental Site

This study was conducted in the experimental greenhouse of the Beijing Academy of Agriculture and Forestry Sciences, Beijing City (39°94′ N, 116°29′ E) from March to July in 2017, 2018, and 2019. The test greenhouse, built in 2016, was a 33 m-wide, three-span steel frame structure with a plantable span of 35 m from north to south. The experimental site is characterized by a temperate continental climate, with mean annual air temperature and precipitation of 11.1 °C and 500–600 mm, respectively. The soil in the greenhouse was sandy loam soil, the bulk density was 1.40 g·cm^{-3}, the field capacity was 0.28 m^3·m^{-3}, and the organic matter was 15.9 g·kg^{-1}.

Eggplant "Heibao" was used in the experiment. The seedlings were transplanted at the three-true-leaf stage. The planting beds were prepared 0.8 m apart and were 0.7 m wide at the top. Two rows of eggplants were transplanted into each planting bed. Plants were spaced 0.45 m apart within rows and the rows were 0.5 m apart. Transparent plastic film with a width of 1.2 m was placed on the soil surface of the planting bed to cover two rows. Eggplant seedlings were transplanted on 7 March, 5 March, and 3 March, and harvested on 28 June, 3 July, and 3 July, in 2017, 2018, and 2019, respectively. A drip irrigation system was used for water supply. To ensure adequate soil water content during the eggplant growing season, the cumulative evaporation (E_p) of the plant canopy was measured with an evaporation pan (20 mm in diameter) used for scheduling irrigation in this experiment [18]. The irrigation amount was 0.8 E_p ("0.8" is the evaporation pan coefficient) and the irrigation period was 7–10 days. Nitrogen was applied at a rate of 75 kg N·ha^{-1} as water-soluble compound fertilizer (N:P_2O_5:K_2O = 3:1:6), with three applications at 30, 55, and 80 days after planting. The daily air temperature in the greenhouse showed an increasing trend during the eggplant growing period, with mean values of 23.3, 23.4, and 22.1 °C in the 2017, 2018, and 2019 seasons (Figure 1), respectively. There were similar relative humidity (*RH*) conditions during the study period, with the daily *RH* varying from 26.2% to 93.7% over the 3 years.

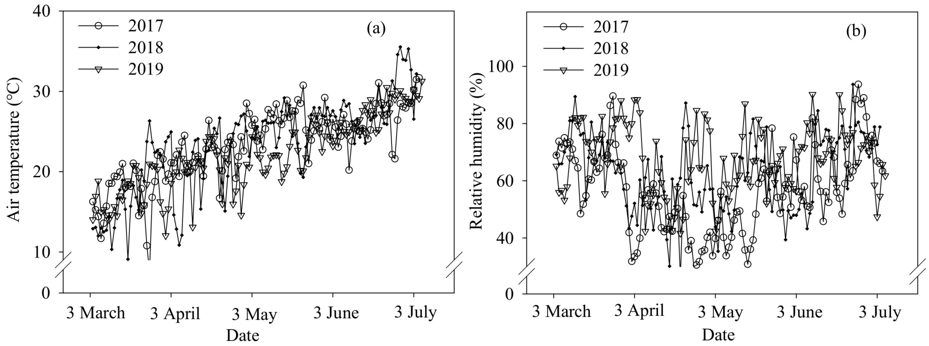

Figure 1. Seasonal variation of air temperature (**a**) and relative humidity (**b**) during the study period in 3 consecutive years.

2.2. Measurements

Daily meteorological data, comprising solar radiation, wind speed, minimum and maximum relative humidities, and minimum and maximum temperatures, were recorded at 10 min intervals with an automatic weather station (Model AG1000, Campbell Scientific, Logan, UT, USA).

The daily ET_c of eggplant was measured by a weighing lysimeter (Beijing Sinton Technology Co., Ltd., Beijing, China). Given that the planting bed surface was completely covered with plastic film in the experiment, the ET_c was mainly due to transpiration [6,19]. The experimental weighing lysimeter was 1 m long, 0.6 m wide, and 0.9 m deep. The system collector was an SDI-12 bus interface and the weighing resolution was 0.01 mm. The weight of the soil column was recorded every 10 min. The ET_c was calculated according to the water balance equation [16]:

$$ETc = \frac{W_{t-1} - W_t}{A \times \rho} + I - Dv \quad (1)$$

where W_{t-1} and W_t (kg) are the weight of soil and water in the lysimeter box at t − 1 and t; A is the surface area of the lysimeter (m^2); ρ is the density of water (g·p cm^{-3}); *I* is the amount of irrigation (mm), and *D*v is the drainage volume (mm).

Three eggplants were randomly selected to measure plant height, leaf length, and maximum width at intervals of 7–10 days. Then, the leaf area index (*LAI*) was determined using an empirical formula [20].

$$LAI = \frac{\sum_{i=1}^{N} Li \times Wi}{S \times D} \times 0.697 \tag{2}$$

where N is the number of samples; L_i is the leaf length (cm); W_i is the maximum leaf width (cm); S is the space between two plants (cm); D is the distance between two rows (cm); and 0.697 is an empirical constant. The eggplant phenological period was observed and recorded during the experiment.

2.3. Crop Coefficient Model

The single crop coefficient model is most commonly used for formulating irrigation schemes of greenhouse-grown vegetable crops [21]. In FAO-56, in the absence of soil water stress, the local K_c is calculated as follows:

$$K_c = \frac{ET_c}{ET_0} \tag{3}$$

where K_c considers the combined impact of soil evaporation and crop transpiration. The actual ET_c can also be estimated as:

$$ET_c = Kc \times ET_0 \tag{4}$$

ET_0 was determined by the modified Penman–Monteith equation in the study and was calculated as follows:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{1694}{T+273}(e_s - e_a)}{\Delta + 1.64\gamma} \tag{5}$$

where Δ is the slope of the vapor pressure curve (kPa·°C^{-1}), R_n is the net radiation at the crop surface (MJ·m^{-2}·d^{-1}), T is the mean daily air temperatures (°C), G is the soil heat flux density (MJ·m^{-2}·d^{-1}), e_s is the saturation vapor pressure (kPa), e_a is the actual vapor pressure (kPa), and γ is the psychrometric constant (kPa·°C^{-1}).

The K_c values from FAO-56 are presented for sub-humid regions (minimum relative humidity of 45%) with moderate wind speed. The K_c curve is commonly described with four linear segments, which are defined by FAO-56 as representing the initial, development, mid-season, and end-season periods [7]. However, K_c is likely to vary with environmental conditions and requires adjustment for local experimental conditions at these crop growth stages.

The single crop coefficient correction method considering the effect of relative humidity and wind speed is used to determine K_c values at the initial stage [22]. The calculation formula used is as follows:

$$K_{cini} = K_{cb} + [0.04(U_2 - 2) - 0.004(RH_{min} - 45)] \times \left(\frac{h}{3}\right)^{0.3} \tag{6}$$

where K_{cini} is the adjusted K_c in the initial stage ($K_{c,Adj}$), K_{cb} is the basal crop coefficient recommended in FAO-56 (see Section 2.5), U_2 is the daily wind speed at a height of 2 m (m· s^{-1}), RH_{min} is the daily minimum relative humidity (%), and h is the plant height (m).

The K_c value in the mid-season and end-season stages was adjusted as follows [8]:

$$K_{cmid} = K_{cend} = K_{cb} + [0.04(U_2 - 2) - 0.004(RH_{min} - 45)] \times \left(\frac{h}{3}\right)^{0.3} \tag{7}$$

where K_{cmid} and K_{cend} are the adjusted K_c values in the middle and end stages, respectively.

The value of K_c in the development stage was calculated as follows [7]:

$$K_{ci} = K_{cprev} + \left[\frac{i - \sum(L_{prev})}{L_{stage}}\right](K_{cnext} - K_{cprev}) \quad (8)$$

where i is the day number within the growing season, K_{ci} is the K_c on day i, K_{cprev} is the K_c of the previous stage, K_{cnext} is the K_c of the next stage, L_{prev} is the length of the previous stage, and L_{stage} is the length of the current growth stage.

2.4. Statistical Analysis

The coefficient of determination (R^2), root-mean-squared error (RMSE), mean absolute error (MAE), and index of agreement (d) were used to evaluate the performance of the model [23]:

$$R^2 = \left[\frac{\sum_{i=1}^{N}\left(O_i - \overline{O}\right)\left(P_i - \overline{P}\right)}{\left[\sum_{i=1}^{N}\left(O_i - \overline{O}\right)^2\right]^{0.5}\left[\sum_{i=1}^{N}\left(P_i - \overline{P}\right)^2\right]^{0.5}}\right]^2 \quad (9)$$

$$\text{MAE} = \frac{\sum_{i=1}^{N}|Q_i - P_i|}{N} \quad (10)$$

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}(P_i - O_i)^2}{N}} \quad (11)$$

$$d = 1 - \left(\frac{\sum_{i=1}^{N}(O_i - P_i)^2}{\sum_{i=1}^{N}\left[\left(P_i - \overline{O}\right) + \left(O_i - \overline{O}\right)\right]^2}\right) \quad (12)$$

where P_i and O_i are the predicted and observed data, respectively, N is the number of data points, and $\overline{P}$ and $\overline{O}$ are the respective mean values.

2.5. K_{cb}

The basal crop coefficient (K_{cb}) at the crop development stages was calibrated by minimizing the differences between estimated and measured ET_c for eggplant in 2017. The initial value of K_{cb} was set as 0.6, 1.05, and 0.90 at the initial, mid-season, and end-season stages, respectively, based on data from FAO-56 [7]. The corresponding calibrated values of K_{cb} were 0.21, 1.04, and 0.76. Using the calibrated model parameters, model estimation was performed for K_c and ET_c in the other growth seasons. Figure 2 compares the daily ET_c measured with the weighing lysimeter and that estimated using the crop coefficient model when K_{cb} was determined in 2017. The R^2 value was 0.933, mean absolute error (MAE) was 0.397 mm·d^{-1}, and RMSE was 0.512 mm·d^{-1}.

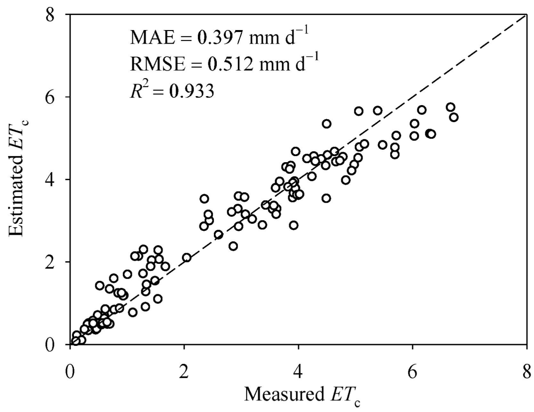

Figure 2. Comparison of measured and estimated crop evapotranspiration (ET_c) for greenhouse-grown eggplant in 2017. The dashed line represents a 1:1 ratio.

3. Results

3.1. Growing Stages and Growth Indicators

The lengths of the growth stages for greenhouse-grown eggplant during the study period in the 2017, 2018, and 2019 growth seasons are summarized in Table 1. Generally, plants showed similar growth development periods in the greenhouse environment for the 3 years. The seasonal dynamics of eggplant plant height and *LAI* during the study period were generally similar among the 3 years. The plant height increased with the progression of the growth period and the maximum height was attained in the end-season stage. The *LAI* increased from the initial stage until the mid-season stage, when it attained maximum values of 3.10, 3.05, and 3.02 in 2017, 2018, and 2019, respectively, and thereafter gradually declined.

Table 1. Duration of the crop development stages and measured growth indicators of greenhouse-grown eggplant in the 2017–2019 growing seasons.

Measured Indicator		Initial Stage	Development Stage	Middle Stage	End Stage
2017	Days/d	20	37	33	24
	Plant height/m	0.11	0.34	0.79	0.94
	*LAI**	0.06	0.91	3.10	2.89
2018	Days/d	19	38	36	28
	Plant height/m	0.12	0.35	0.81	0.96
	LAI	0.06	0.93	3.05	2.96
2019	Days/d	23	34	36	30
	Plant height/m	0.12	0.38	0.83	0.97
	LAI	0.07	0.95	3.02	2.98

Notes: * Leaf area index.

3.2. ET_0

Daily variation in ET_0 in the greenhouse during the study periods in 2017, 2018, and 2019 is shown in Figure 3. The amplitude of seasonal fluctuations of ET_0 was relatively large in this study. The daily ET_0 was generally higher later in the mid-season and late-season stages (i.e., May and June) than early in the growing season (from March to April). Daily ET_0 changed from 0.65 to 5.71 mm, 1.26 to 5.68 mm, and 1.18 to 5.50 mm with means of 3.62 mm, 3.21 mm, and 3.11 mm, respectively, during the study period in 2017, 2018, and 2019, respectively. The cumulative ET_0 over the entire growing season was 412.9, 388.2, and 382.5 mm in 2017, 2018, and 2019, respectively.

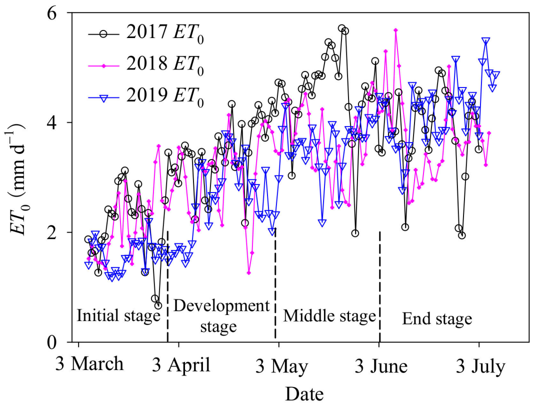

Figure 3. Seasonal variation in reference crop evapotranspiration (ET_0) for greenhouse-grown eggplant during the crop development stages in 3 consecutive years.

3.3. Variation of Kc for Eggplant

The daily local crop coefficient for greenhouse-grown eggplant was determined from the data measured with the weighing lysimeter in 2017, 2018, and 2019. Figure 4 shows the variation in daily local K_c in the 3 years. The fluctuations of local K_c in the different years were similar. The K_c value was relatively stable during the initial stage and began to increase rapidly during the development stage. The maximum K_c value was attained in the mid-season stage, and thereafter gradually decreased in the end-season stage.

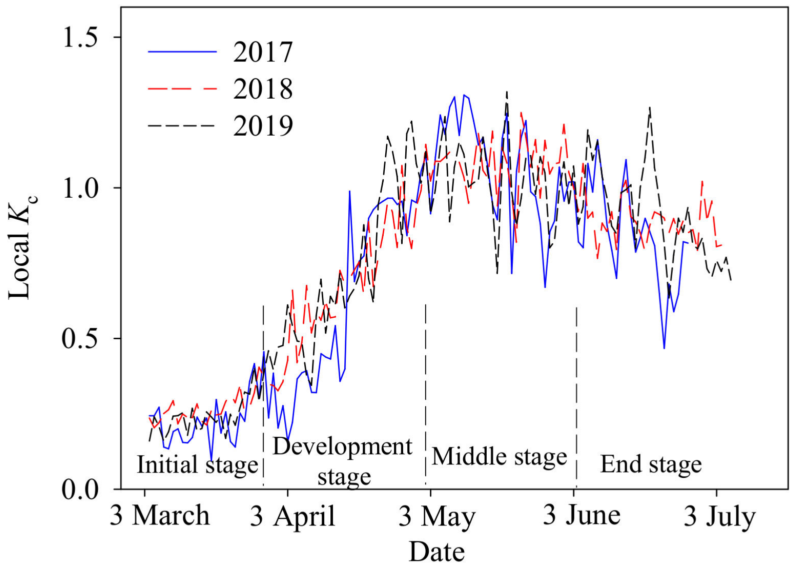

Figure 4. Variation in daily local crop coefficient (K_c) of greenhouse-grown eggplant in the 2017, 2018, and 2019 seasons.

The recommended K_c values from FAO-56 ($K_{c,FAO}$), and adjusted ($K_{c,Adj}$) and locally developed K_c ($K_{c,Loc}$) at the initial, development, mid-season, and end-season stages for eggplant are summarized in Table 2. Good agreement was observed between $K_{c,Adj}$ and $K_{c,Loc}$ at the four growth stages in the 3 years. At the initial stage, the means of $K_{c,Adj}$ and $K_{c,Loc}$ for the 3 years were 0.20 and 0.23, respectively, which were 66.3% and 61.8% lower than that of $K_{c,FAO}$, respectively. In the development, mid-season, and late-season stages, the means over the 3 years for $K_{c,FAO}$ were 0.64, 1.01, and 0.85 and those for $K_{c,Loc}$ were 0.62, 1.05, and 0.87, respectively. Figure 5 shows the results of a linear regression analysis between $K_{c,Loc}$ and $K_{c,Adj}$. The data points were close to the 1:1 line for the 2017, 2018, and 2019 seasons, with R^2 of 0.873, 0.901, and 0.897 ($p < 0.01$), respectively.

Table 2. Locally developed crop coefficient ($K_{c,Loc}$) and adjusted crop coefficient ($K_{c,Adj}$) for greenhouse-grown eggplant in the 2017–2019 growing seasons.

Kc	Growth	Season 2017	Season 2018	Season 2019	Average
$K_{c,FAO}$ [a]	Initial	0.60	0.60	0.60	0.60
	Development	/	/	/	/
	Middle	1.05	1.05	1.05	1.05
	End	0.90	0.90	0.90	0.90
$K_{c,Adj}$ [b]	Initial	0.20	0.19	0.21	0.20 ± 0.01
	Development	0.64	0.63	0.66	0.64 ± 0.01
	Middle	1.02	1.01	1.00	1.01 ± 0.01
	End	0.84	0.84	0.87	0.85 ± 0.02
$K_{c,Loc}$ [c]	Initial	0.20	0.25	0.24	0.23 ± 0.03
	Development	0.57	0.61	0.69	0.62 ± 0.06
	Middle	1.07	1.07	1.02	1.05 ± 0.03
	End	0.84	0.88	0.90	0.87 ± 0.03

Notes: [a] The values were reported in FAO-56 [7]. [b] The values were adjusted based on a greenhouse environment, as shown in Equations (6)–(8). [c] Defined as the ratio between observed ET_c and ET_0 at four distinct growth stages. Values are mean ± SE of each growth stage in 3 years.

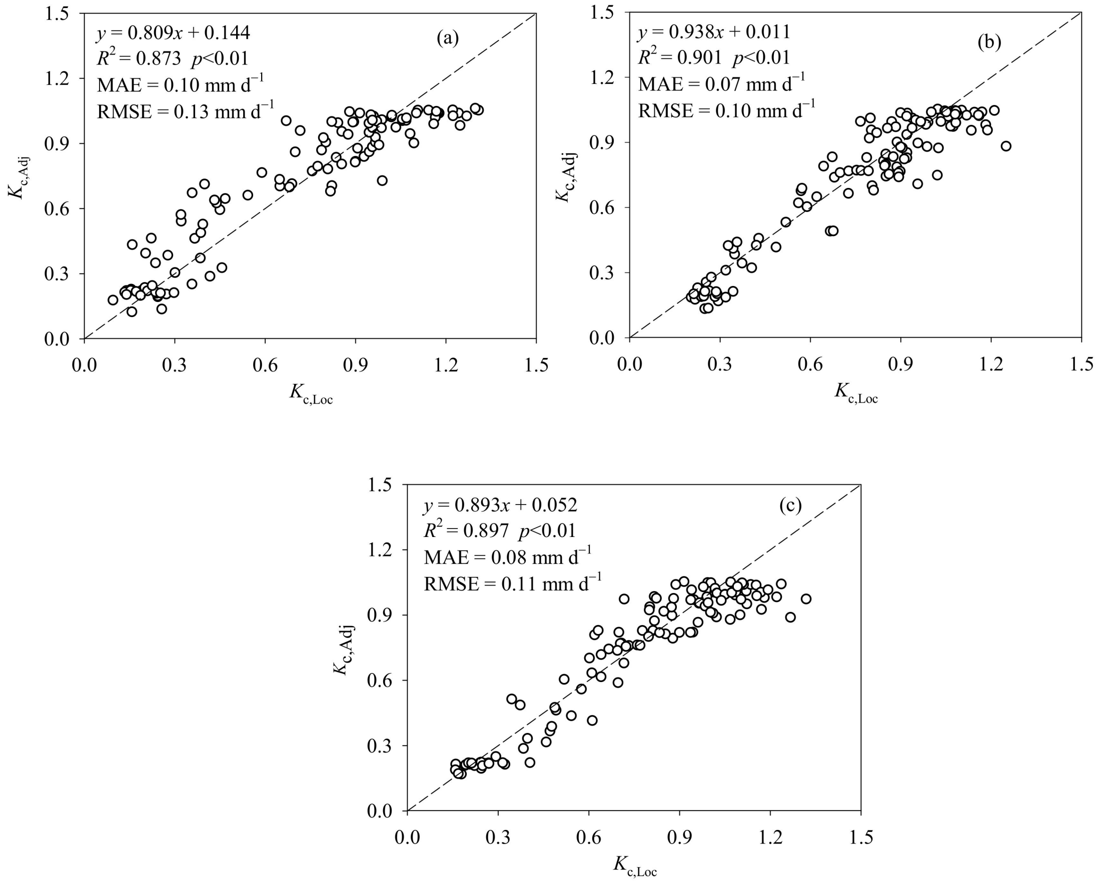

Figure 5. Comparison of local crop coefficient developed ($K_{c,Loc}$) and adjusted crop coefficient ($K_{c,Adj}$) for greenhouse-grown eggplant in the 2017 (**a**), 2018 (**b**), and 2019 (**c**) growing seasons. The dashed line represents a 1:1 ratio.

3.4. Estimation of ET_c

Figure 6A,C shows the comparison of measured daily ET_c and that estimated by the proposed single crop coefficient method in 2018 and 2019. The verification of measured and estimated ET_c was consistent, which increased from transplanting, peaked during the mid-season stage, and decreased gradually during the end-season stage. The estimated ET_c accumulated over the entire growing season was 304.0 mm and 308.9 mm in 2018 and 2019, respectively, and 10.2 mm and 6.58 mm lower than the measured value determined using the lysimeter. The measured ET_c values were linearly fitted with the model-calculated values in 2 years. The calculated and measured values of ET_c for greenhouse-grown eggplant were concordant, the regression coefficient was close to 1, and the R^2 values were 0.947 and 0.943 ($p < 0.01$) in 2018 and 2019, respectively (Figure 6B,D).

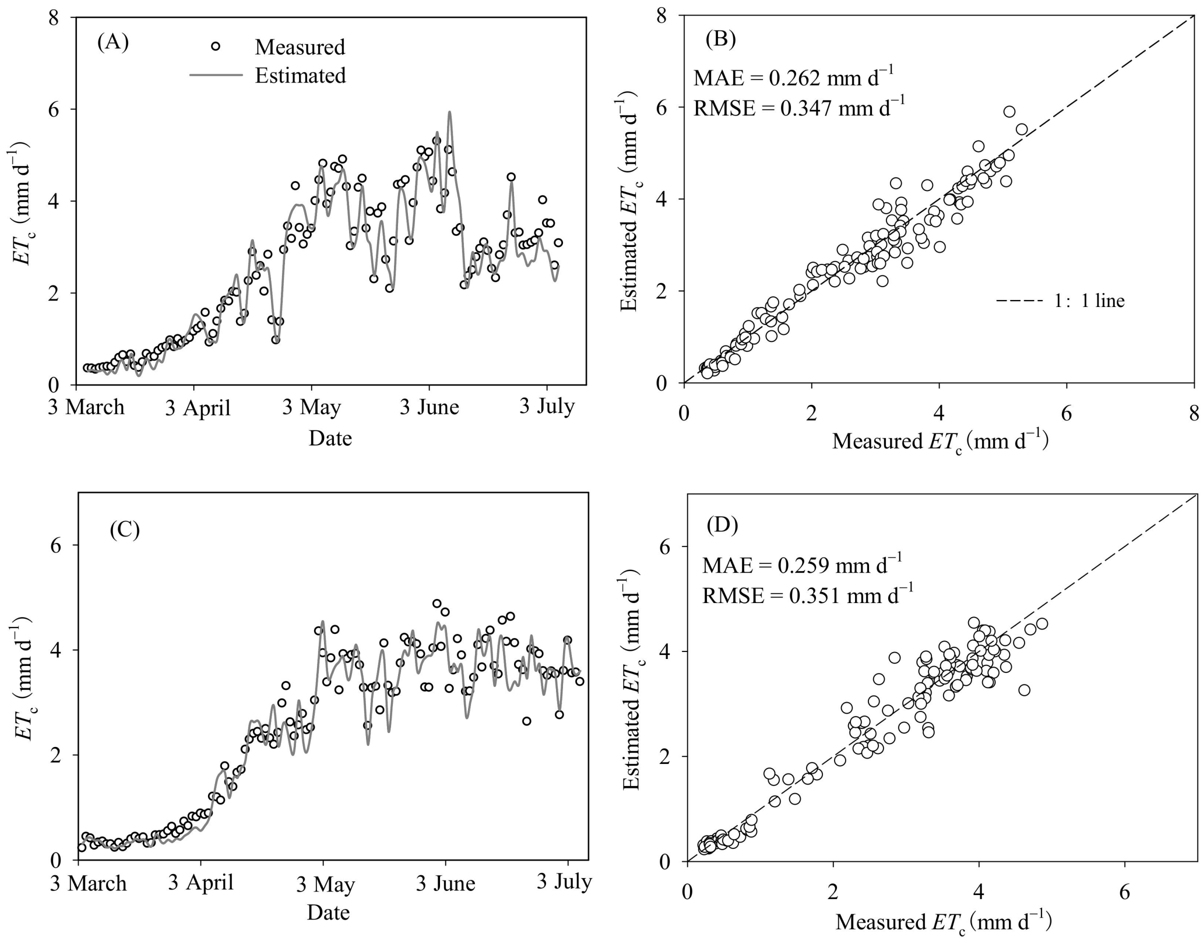

Figure 6. Comparison of measured and estimated crop evapotranspiration (ET_c) of greenhouse-grown eggplant in the 2018 (**A**,**B**), and 2019 (**C**,**D**) seasons.

3.5. Statistical Analysis of Estimated and Measured ET_c

The results of statistical analysis of the estimated and measured ET_c at different developmental stages of greenhouse-grown eggplant are shown in Table 3. The mean daily measured ET_c at the different growth stages changed from 0.49 to 4.04 mm·d^{-1} in 2018 and from 0.38 to 3.73 mm·d^{-1} in 2019. The mean daily estimated ET_c was 0.38–3.83 mm·d^{-1} and 0.34–3.68 mm·d^{-1} in 2018 and 2019, respectively. The minimum values of MAE and RMSE were observed in the initial stage and were 0.06–0.11 mm·d^{-1} and 0.09–0.11 mm·d^{-1}, respectively, in the 2 years. The maximum values of RMSE and MAE were observed in the end-season stage and were 0.43–0.48 mm·d^{-1} and 0.32–0.39 mm·d^{-1}, respectively, in the 2 years. The d of each growth stage was greater than 0.90, and d was highest at the initial stage, followed by the development stage. From the perspective of the entire growth period of eggplant, the crop coefficient model underestimated ET_c compared with the measured ET_c, and d was greater than 0.98.

Table 3. Statistical indicators of measured and estimated crop evapotranspiration (ET_c) for greenhouse-grown eggplant in 2018 and 2019.

Season	Statistical Indicators	Initial	Development	Middle	End	Whole
2018	Measured ET_c(mm·d^{-1})	0.49	1.86	4.04	3.21	2.60
	Estimated ET_c(mm·d^{-1})	0.38	1.94	3.83	3.07	2.51
	MAE(mm·d^{-1})	0.11	0.22	0.20	0.39	0.26
	RMSE(mm·d^{-1})	0.11	0.29	0.31	0.48	0.35
	d*	0.99	0.98	0.98	0.93	0.98
2019	Measured ET_c(mm·d^{-1})	0.38	1.79	3.72	3.73	2.57
	Estimated ET_c(mm·d^{-1})	0.34	1.75	3.68	3.63	2.51
	MAE(mm·d^{-1})	0.06	0.27	0.32	0.32	0.26
	RMSE(mm·d^{-1})	0.09	0.32	0.40	0.43	0.35
	d	0.99	0.98	0.97	0.96	0.98

Notes: * Index of agreement.

4. Discussion

In this study, the maximum and minimum local K_c values were observed in the mid-season stage and the initial stage, respectively. The local K_c showed lower dispersion in the initial stage, with averages of 0.20, 0.25, and 0.24 in 2017, 2018, and 2019, respectively. This finding was attributed to the plastic-film mulching of the planting bed and that the *LAI* was less than 1 (Table 1). Orgaz et al. [24] reported similar results that the K_c of greenhouse-grown melon was approximately 0.2 during the crop's initial stage when the *LAI* value was close to zero. Pereira et al. [11] reported that the average K_c during the initial stage can be represented by a horizontal line because the variation with time is small. The local K_c value increased rapidly with time and peaked in the mid-season stage (Table 2). Previous studies indicated that the variation in K_c at the mid-season stage is mainly due to the increase of *LAI* [25–27]. In the current study, the maximum *LAI* was also observed in the mid-season stage and the values were all greater than 3.0 in the 3 years. In the end-season stage, K_c gradually decreased. This was because the leaves began to age and senesce at the end of the growing period, which resulted in a lower *LAI*. Ge et al. [28] showed that eggplant K_c as a whole exhibited a single peak curve change in a greenhouse environment, and ranged from 0.78 to 1.48. Wang et al. [5] reported that, under a suitable irrigation scheme, the K_c ranges for eggplant were 0.21–0.46, 0.62–0.94, and 0.70–0.92 at the seedling stage, flowering stage, and picking stage, respectively. These results indicated that the variation in K_c of greenhouse-grown eggplant under different experimental conditions was consistent, but the K_c values differed considerably among studies. Possible reasons for this are as follows: (1) the ET_0 calculation methods differ; (2) the observation methods for ET_c differ; (3) the eggplant growing season and planting time differ; and (4) the field management practices differ (e.g., irrigation and fertilization schemes) [26,29].

In the current study, a significant linear relationship between $K_{c,Adj}$ and $K_{c,Loc}$ was observed, with R^2 values of 0.873, 0.901, and 0.897 in 2017, 2018, and 2019, respectively. These results demonstrated that K_c adjusted based on the local climate showed good agreement with the local value determined using the lysimeter. These results were also in agreement with those of Gong et al. [30], who observed that $K_{c,Adj}$ and $K_{c,Loc}$ were 1.09 and 1.13, respectively, in the mid-season stage for tomato. However, in the present study, $K_{c,Adj}$ and $K_{c,Loc}$ were always lower than $K_{c,FAO}$ in the three consecutive years, especially in the initial stage. This may be attributed to the higher relative humidity and lower wind speed in the greenhouse environment, whereas $K_{c,FAO}$ was suggested based on standard climatic conditions (RH_{min} of approximately 45% and U_2 of approximately 2 m·s^{-1}). Similar results were reported by Gong et al. [30] and Qiu et al. [31] in studies using tomato and green pepper, respectively. The 3-year average values of $K_{c,Adj}$ and $K_{c,Loc}$ at the initial stage were 0.20 and 0.23 (Table 2), respectively, which decreased by 66.3% and 61.8% compared with the $K_{c,FAO}$ value. In addition, Muniandy et al. [26] showed that the experimental K_c values for sweet pepper and cucumber were lower than the FAO-56-recommended values, and the maximum differences were 18.9% and 23.5%, respectively. These results suggest that the FAO-56-recommended K_c value cannot be directly applied to the greenhouse environment, and it is necessary to adjust the K_c value based on the actual environment. In addition, previous studies have observed that the K_c developed in a particular region is not applicable in other regions owing to the difference in climate [11,26]. Although the $K_{c,Adj}$ and $K_{c,Loc}$ values were much lower than the FAO-56-recommended value (K_{cb}) in the initial stage, a large difference was not observed during the mid-season and end-season stages (Table 2). This could have been due to the effects of the plastic-film mulch. The plastic film almost completely covered the soil wetted by the drip emitters in the present experiment and its most direct effect was to act as a barrier to reduce soil water evaporation. Zhao et al. [32] showed that, compared with the non-mulched treatment, mulching in a field experiment significantly reduced K_c by 55.3% during the initial stage, whereas in the mid-season and end-season stages, K_c was decreased by 5.7% and 9.7%, respectively. Many studies have reported that plastic-film mulching and soil temperature are the main factors that affect K_c during the initial stage [7,32]. During the development, mid-season, and end-season stages, with the increase in crop canopy cover, the effect of film mulching on the energy budget is weakened and K_c is mainly affected by LAI [32]. Film mulching has little effect on evapotranspiration when the LAI is greater than 3.0 because it reduces evaporation and increases transpiration [33].

Compared with ET_c estimation based on other models (e.g., two-layer Shuttleworth–Wallace), the crop coefficient model is the simplest and estimates ET_c with high accuracy if K_c is adjusted based on the actual environment [22,30,34]. In this study, the crop coefficient model accurately estimated the daily ET_c of greenhouse-grown eggplant during each growth period, with a MAE of 0.11–0.39 mm$\cdot$d^{-1} in 2018 and 0.06–0.32 mm$\cdot$d^{-1} in 2019, and RMSE of 0.11–0.48 mm$\cdot$d^{-1} in 2018 and 0.09–0.43 mm$\cdot$d^{-1} in 2019 (Table 3). Yan et al. [35] reported that the RMSE, R^2, and model efficiency coefficient of the crop coefficient model for prediction of spring–summer cucumber daily ET_c were 0.41 mm $\cdot$ d^{-1}, 0.95, and 0.93, respectively. These results demonstrated that daily ET_c under a greenhouse environment calculated with the crop coefficient model was in agreement with the measured values. Similar results have been validated in other crops under different cultivation conditions, including maize, rice, and grapes [12,25,36]. However, in the present experiment, daily ET_c was underestimated by the crop coefficient model, which may have been due to the following factors. (1) A plastic-film mulch covered the experimental plot, but may have caused damage to the roots of the plants during the experimental period, which may have led to the increase in measured evapotranspiration [31]. (2) The crop coefficient model used in this study did not consider the effect of the soil evaporation coefficient, but was unable to completely avoid the occurrence of soil evaporation in practice; this was also an important reason why the adjusted K_c in each growth period was lower than the local K_c (Table 2). (3) The high relative humidity in the greenhouse environment is among the reasons why the daily ET_c estimated value was lower than the measured value [30]. Previous research has shown that the ET_c of greenhouse-grown tomato estimated by a modified crop coefficient method is 12.2–24.8% lower than the measured values [37]. (4) Although a weighing lysimeter is widely used to measure ET_c because of the limited representative area, the ET_c measurement value is usually higher than the model estimation value [12]. In this study, seasonal lysimeter-based eggplant ET_c values presented similar variations in 2018 and 2019, indicating that eggplant water requirements were consistent among the years. The total ET_c determined with the crop coefficient model was 306.5 mm on average in the 2 years (2018 and 2019), which was lower than the measured value, and the R^2 value was greater than 0.9, indicating that the crop coefficient method could explain most of the total variation in measured ET_c. High values of d (>0.90) showed that the estimated daily ET_c was statistically similar to the measured values. Thus, overall, the crop coefficient method provided satisfactory results for estimating ET_c at each growth stage of greenhouse-grown eggplant, and offers an effective method for accurately determining the dynamic water demands of greenhouse-grown eggplant.

5. Conclusions

In this study, the variation in K_c for spring greenhouse-grown eggplant at different crop development stages was investigated and the performance of a crop coefficient model for estimating ET_c was assessed. The local K_c ($K_{c,Loc}$) of greenhouse-grown eggplant showed the same seasonal changes and ranges of 0.20–0.25, 0.57–0.69, 1.02–1.07, and 0.84–0.90 for the initial, development, mid-season, and end-season stages, respectively, in the three consecutive years. $K_{c,Adj}$, adjusted based on the actual environment, showed good agreement ($R^2 > 0.87$) with $K_{c,Loc}$ measured using the lysimeter. However, the $K_{c,Adj}$ and $K_{c,Loc}$ values were consistently lower than $K_{c,FAO}$ in the 3 years, with substantial differences of 66.3% and 61.8% observed in the initial stage. The crop coefficient model accurately estimated the daily ET_c of greenhouse-grown eggplant during each growth period, with MAE of 0.11–0.39 $\mathrm{mm \cdot d^{-1}}$ and 0.06–0.32 $\mathrm{mm \cdot d^{-1}}$, and RMSE of 0.11–0.48 $\mathrm{mm \cdot d^{-1}}$ and 0.09–0.43 $\mathrm{mm \cdot d^{-1}}$, for the 2018 and 2019 growing seasons, respectively.

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