Evapotranspiration Model-based Scheduling Strategy for Baby Pakchoi Irrigation in Greenhouse

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Abstract. Water management is one of the most important operations in greenhouse baby leaf production. However, growers mainly irrigate the plants based on experience, which generally leads to yield loss, uneven quality, and low water-use efficiency. This study evaluated four evapotranspiration (ET) models, such as Radium, Penman methods, FAO Penman-Monteith, and Priestley-Taylor, for irrigation strategy by predicting the ET level of greenhouse baby pakchoi [*Brassica rapa* L. ssp. *chinensis* (L.) Hanelt] under different plant densities (72-, 128-, 200-, and 288-plug tray). Among environmental factors, net radiation and photosynthetically active radiation (PAR) had the highest correlation with ET, with R^2 of 0.93 and 0.94, respectively. Plant growth period was divided into different stages according to canopy development and substrate surface coverage. The corresponding crop coefficient (K_c) was introduced into ET prediction models. The result shows overestimation of ET_c (crop evapotranspiration) by the Radium and Penman methods. FAO Penman-Monteith and Priestley-Taylor methods performed the best with $R^2 \approx 0.7$ for all planting densities. These two methods are recommended for greenhouse irrigation scheduling in baby pakchoi production.

With growing interest in local food production using greenhouse technology, fresh and nutritious baby leaf greens are becoming increasingly popular among consumers (Kroggel et al., 2012). Plug trays filled with substrate is used for greenhouse baby leaf production with ebb-and-flow (E&F) irrigation systems (Danfeng et al., 2013). E&F irrigation is characterized as producing uniform plants, with a short production cycle, high water- and fertilizer-use efficiency, and adequate plant quality (Yang et al., 2018). In production practice, the quality of baby leaf is sensitive to substrate water content. Water deficiency or overirrigation can have a significantly negative effects on baby leaf plant physiology (Guo et al., 2017). Therefore, it is critical to manage irrigation precisely in greenhouse baby leaf production to improve production quality and water-use efficiency.

Greenhouse growers typically irrigate crops based on their personal experience,

which normally leads to uneven product quality and waste of water resources. Few studies have reported the irrigation scheduling strategy for leafy greens by using subirrigation such as E&F irrigation. Irrigation frequency and flood time were identified as two key factors in the E&F irrigation strategy (Yang et al., 2018). In substrate type, flooding depth and time have also been studied to optimize E&F irrigation (Anlauf et al., 2012).

Different methods have been developed for greenhouse irrigation management. The main approaches include soil-based, plant-based, and climate-based methods (Jones, 2004). The monitoring of water content or water potential in growing media is a fast and reliable way to establish irrigation scheduling. However, sampling position and sensor cost limit the application of this method in baby leaf production in trays. Weighting the tray could also accurately measure the water amount, but this method has high labor costs. The plant phenotyping technique can be used to determine plant response to different water content with cameras scanning the plants (Guo et al., 2017). In this way, irrigation time could be indicated by plant phenotypes, but the irrigation amount is difficult to quantify.

Irrigation water requirements can be defined as the quantity of irrigation water required to produce the desired crop yield and quality and to maintain an acceptable water balance in the substrate. Previous studies showed that water requirement for different crops was highly related to the light radiation, vapor pressure deficit (VPD), substrate characteristics, and crop growth characteristics in greenhouse (Orgaz et al., 2005; Sumner and

Jacobs, 2005). Predicting ET is a commonly used indicator of irrigation decision-making, which is the main index for determining the optimal crop water and fertilizer management (Allen et al., 1998).

In greenhouses, the soil, crop, and environment are regarded as a continuum to study the water absorption through crop roots, the transport of water in crops, and the transport of water inside plants (Campbell and Norman, 2000). In this process, more attention should be paid to crop response to irrigation and greenhouse microclimate, as well as the combination of agronomy, plant physiology, environmental control, engineering technology, and other factors. Optimized ET models and greenhouse thermal environment management enhance greenhouse energy conservation, reduce water consumption, and improve crop quality and yield. Several studies have investigated ET prediction in greenhouse. The model varies across different regions, climates, and greenhouse environments; hence, the application is often limited. Whether it is applicable in other regions or other greenhouses, systemic calibration and validation should be replicated in more diverse greenhouse climates.

The use of the ET model in a greenhouse environment is different from the open field because of the variation and dynamic climate. Existing studies about ET prediction in greenhouse mainly focus on vegetables such as tomato, cucumber, and eggplants. Seasonal ET of melon, green beans, watermelon, and pepper was studied in an unheated plastic greenhouse (Orgaz et al., 2005). Three models (Stanghellini, Penman-Monteith, and Takakura) were compared to simulate the ET of bell pepper and tomato. Results showed that the Stanghellini model has the best overall performance under all conditions evaluated, but there were no significant differences between the three models. (Villarreal-Guerrero et al., 2012). Several models developed to estimate ET in greenhouses have been reviewed, suggesting greenhouse ET models should be selected depending on the type, location, and crop type (Karaca et al., 2018). In another review article, 10 models used in different type of greenhouses were compared, and the FAO Penman model was recommended for plastic greenhouse ET estimation (Ilahi, 2009). To date, limited studies have been done on ET research on baby leaf vegetables in greenhouse production.

There have been several investigations into the ET modeling focused on leafy greens or short plants in greenhouse. Floating seedling water evaporation in greenhouse was investigated using an ET model based on the Penman formula under artificial lighting conditions (Zeng et al., 2015). A canopy transpiration model for greenhouses was established based on the Penman-Monteith transpiration model to simulate the ET of pakchoi in a plastic greenhouse covered with insect proof net (Jun et al., 2009). ET of turfgrass in greenhouse was studied with the FAO-56 Penman-Monteith and a 20-cm evaporating

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pan method with adequate correlation between actual ET (ET_a) and reference ET (ET_0) predicted by the FAO Penman-Monteith model (Xue et al., 2008). Andersson evaporimeters, FAO Radiation, and FAO Penman-Monteith equations were compared with estimate lettuce ET in greenhouse (Casanova et al., 2009). The Priestley-Taylor model was evaluated for estimating greenhouse tomato with drip irrigation, but no research was found for greenhouse leaf vegetables (Valdés-Gómez et al., 2009). FAO-24 Penman and Priestley-Taylor were compared with FAO-56 Penman-Monteith in Venlo-type greenhouse ET prediction with the conclusion that the application of FAO-56 Penman-Monteith in the greenhouse was unsatisfactory and modification was needed to adjust the Aerodynamic resistance (Eitzinger et al., 2007). The Penman-Monteith and Priestley-Taylor models can directly estimate ET_a but require canopy resistance. These variables depend on leaf area index, soil water availability, elevation, soil characteristics, VPD, and solar radiation (Sumner and Jacobs, 2005). Water management of greenhouse tray seedling leafy vegetables lacks a basis for decision-making, relying mostly on empirical selection. ET model studies rarely involve greenhouse seedling leafy vegetables.

The objectives of this study were 1) to assess the applicability of four ET prediction methods in greenhouse baby pakchoi production; and 2) to investigate the performance of the ET prediction models on baby pakchoi irrigation management under different plant densities. Climate-based methods could provide a potential solution for greenhouse smart irrigation scheduling.

Materials and Methods

Experiment condition and greenhouse management

The greenhouse experiments were conducted from 1 Sept. to 23 Sept. on baby pakchoi, cv. Huawang. The seedlings were grown in a multispan plastic greenhouse located at Jiading, Shanghai (lat. 31.36°N, long. 121.21°E, 17 m altitude). The experimental greenhouse was a GSW-8430 type four span greenhouse with single layer polyethylene film. The greenhouse had total area of 3974 m², with top height of 5.2 m, span of 8 m, and gutter height of 3 m. The greenhouse was equipped with 70% internal shading screen, electrical top windows, manual side windows, E&F seedbed, and irrigation control system. The greenhouse climate was controlled by manual ventilation and shading. During the experiment, manual ventilation was used several times per day according to the climate conditions. The side window was kept open during the experiment period (late summer in Shanghai) to maintain the natural ventilation. The top window was opened when the air temperature was >25 °C and closed at night and on cloudy days. E&F irrigation operated twice per day at 0800 HR and 1600 HR, and each irrigation lasted ≈7 min (flood

time). In the preexperiment, three irrigation frequencies were compared, and the result showed that twice daily irrigation could fully saturate the substrate. During this experiment, the baby pakchoi were grown in four types of tray (72-, 128-, 200-, and 288-plug trays, tray size 54 × 28 cm). Each group had 21 trays and three random group replications.

The pakchoi was sown into plug trays filled with commercial seedling substrate (Jinhai Agriculture Technology Inc., Hangzhou, China) on 1 Sept. After germinating for 72 h under 25 °C and 95% relative humidity (RH) in the germination room, trays with seedlings were transferred to the greenhouse and irrigated with nutrient solution (EC = 0.5 mS/cm and pH 5.5 to 6.5). Trays were placed on movable E&F benches, 0.7 m above-ground.

Variables measurement

The PAR, air temperature, and RH were measured by sensors with a HOBO 3.0 climate station (Onset, Bourne, MA) located 2 m aboveground. Net radiation was measured by four-component net radiometer (NR01; Hukseflux, the Netherlands) 2.5 m above ground level. All sensors were scanned at 5-s intervals, and 5-min averaged readings were recorded. Plant biomass was obtained every 2 d until baby pakchoi was harvested on 23 Sept. Average daily actual ET of seven trays from different treatments (72-, 128-, 200-, and 288-plug trays) was measured as ET_a according to the water balance method (Yuan et al., 2001). ET_a was measured as the mean weight differences of seven trays before and after each irrigation at 0800 HR and 1600 HR with electronic scale (Scale: 0 to 6 kg, Accuracy: 0.1 g, D11; Sanfeng, Shanghai, China). Leaf area was scanned at 2-d intervals by using a Canon digital scanner (CanoScan LiDE 120; Canon Inc., Tokyo, Japan), and the images were analyzed with ImageJ to extract the leaf area data (Schneider et al., 2012). The total leaf area per plant from different groups were obtained to get the leaf area index (LAI). LAI was calculated as the ratio of one-sided leaf area to the total tray area (54 × 28 cm). Growth rate of LAI was calculated by the percentage increase at 2-d intervals during the experiment.

Evapotranspiration model description

The application of ET model relies on the availability of data, which is limited by the measurement equipment, expertise, climate, and historical data. Therefore, models reported in previous studies with fewer inputs and better greenhouse performance were selected (Ilahi, 2009). Two physical ET models (Penman model and FAO Penman-Monteith model) and two radiation-based models (Priestley-Taylor model and simplified radiation model) were evaluated in this study for their applicability in greenhouse leaf vegetable irrigation practice. Detailed information on the models is provided in Table 1, together with description and value set in this study of variables and constants required by the four models.

The Penman method. The first model estimating evaporation for open water, bare soil, and grass was developed by Penman (Penman and Keen, 1948). Penman's equation requires daily mean temperature, wind speed, air pressure, and solar radiation to predict evaporation. The equation is as follows:

$$ET_0 = \frac{\Delta(R_n - G)/\lambda + \gamma(2.626 + 1.381u_2)(e_s - e_a)}{\Delta + \gamma}, \quad [1]$$

where

$$e^0(T) = 0.6108 \exp\left(\frac{17.27T}{T + 237.3}\right), \quad [2]$$

$$e_s = \frac{e^0(T_{max}) + e^0(T_{min})}{2}, \quad [3]$$

$$e_a = \frac{RH_{mean}}{100} \left[\frac{e^0(T_{max}) + e^0(T_{min})}{2} \right], \quad [4]$$

For the calculation of ET_0 in Penman and other models, the slope of the saturation vapor pressure temperature relationship, Δ , is required. The value is calculated as:

$$\Delta = \frac{4098 \left[0.6108 e^{\left(\frac{17.27T_a}{T_a + 237.3} \right)} \right]}{(T_a + 237.3)^2}, \quad [5]$$

In addition, the psychrometric constant is calculated as:

$$\gamma = \frac{c_p P}{\epsilon \lambda} = 0.665 \times 10^{-3} P, \quad [6]$$

$$P = 101.3 \left(\frac{293 - 0.0065z}{293} \right)^{5.26}, \quad [7]$$

The FAO Penman-Monteith model. Developed from Penman model, FAO Penman-Monteith is the most commonly used model and simulates a reference crop of 0.12 m in height, with a surface resistance of 70 s/m and an albedo of 0.23 (Allen et al., 1998). This method estimates evaporation from an extensive surface of green grass cover of uniform height, actively growing, completely shading the ground and under nonlimited soil water. The Penman-Monteith equation for the calculation of daily ET_0 (mm·d⁻¹) is as follows:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}, \quad [8]$$

Priestley-Taylor model (PT, 1972). On the basis of equilibrium evaporation, Priestley and Taylor proposed a model for estimating evapotranspiration under the assumption of no-flat flow conditions by observing meteorological data of large-area saturated land surface (Priestley and Taylor, 1972). A dimensionless empirical multiplier, $\alpha_{PT} = 1.26$, was used to replace the aerodynamic term of

Table 1. Variables and constants used in these evapotranspiration (ET) models.

Symbol	Name	Value	Unit	Description
Universal constants				
λ	Lambda	2.45	MJ·kg ⁻¹	Latent heat of vaporization = 2.45 MJ·kg ⁻¹ at 20 °C
S	Stefan-Boltzmann constant	4.903×10^{-9}	MJ·K ⁻⁴ ·m ⁻² ·d ⁻¹	Stefan-Boltzmann constant
G	Soil heat flux	0	MJ·m ⁻² ·d ⁻¹	G is negligible for daily time step
c_p	Constant pressure	1.013×10^{-3}	MJ·kg ⁻¹ ·°C ⁻¹	Specific heat at constant pressure
ε	Epsilon	0.622		Ratio molecular weight of water vapor/dry air
Site special constants				
Z	Elevation	17	m	The ground elevation above mean sea level = 17 m for experiment greenhouse
P	Atmospheric pressure	101.25	kPa	The atmospheric pressure at Shanghai
γ	Psychrometric constant	0.0673	kPa·°C ⁻¹	The psychrometric constant calculated by P
u_2	Wind speed	1	m·s ⁻¹	Daily wind speed at 2 m
Variables				
ET_o	Reference ET	Output data	mm·d ⁻¹	Daily reference evapotranspiration calculate by the models
R_n	Net radiation	Input data	MJ·m ⁻² ·d ⁻¹	The net incoming solar radiation at the evaporative surface
T	Air temperature	Input data	°C	Measured hourly air temperature in the greenhouse
RH	Relative humidity	Input data	%	Measured hourly relative humidity in the greenhouse
e_s	Saturation vapor pressure	By calculation	kPa	Daily saturation vapor pressure
e_a	Actual vapor pressure	By calculation	kPa	Daily actual vapor pressure
Δ	Slope vapor pressure curve	By calculation	kPa·°C ⁻¹	The slope of vapor pressure curve, daily value decided by daily temperature
Coefficient for specific model				
α_{pt}	AlphaPT	1.26		AlphaPT for Priestley-Taylor coefficient = 1.26

Universal constants were used for all models. Site special constants were used specifically for the experiment location. α_{pt} was used only in Priestley-Taylor model.

Penman-Monteith equation. The PT method was widely used to calculate the ET_o , especially when weather inputs for the aerodynamic term (RH, wind speed) are unavailable. The equation is given as:

$$ET_o = \frac{\alpha_{PT}\Delta(R_n - G)}{\lambda(\Delta + \gamma)}, \quad [9]$$

Simplified radiation sum model (Radsum, 2016). A solar radiation sum model was developed for the reasonable approximation of ET_o estimated by equating the latent heat of vaporization to net radiation (Waller and Yitayew, 2016). This radiation model works well during sunny days in the arid climate without water vapor transfer limitation, and the simplified model was implemented in some commercial greenhouse irrigation software. The equation is given as:

$$ET_o = \frac{R_n}{\lambda}, \quad [10]$$

Single crop coefficient (K_c) method was used according to FAO-56 (Allen et al., 1998). Crop evapotranspiration, ET_c , is calculated as the product of the reference crop evapotranspiration, ET_o , and K_c . The equation is

$$ET_c = K_c ET_o, \quad [11]$$

Crop type and growth stages are the major factors influencing the value of K_c , which is strongly related to the substrate surface area covered by the crop canopy and to LAI.

Evaluation of model performance

The R^2 and Akaike information criterion (AIC) were used for comparing the models. The R^2 value measures how well the model results fit the actual value, with the value close to 1 indicating more variance explained by the model. AIC is a technique based on in-sample fitness to estimate the likelihood of a model, which is used further to estimate the

predicted values. A good model is one that has the minimum AIC compared with all the other models (Akaike, 1974).

The average daily ET_c were calculated by the four models with input variables including daily environment data, such as temperature, radiation, humidity, and wind speed. R language program software with the Evapotranspiration package was used for such calculations (Guo et al., 2016).

The accuracy of the models for predicting the average daily ET_c are assessed by statistical indices, mean absolute percentage error (MAPE), and root mean squared error (RMSE) calculated as:

$$MAPE = \frac{\sum_{i=1}^n \frac{|P_i - O_i|}{O_i}}{n} \times 100, \quad [12]$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (P_i - O_i)^2}{n}}, \quad [13]$$

where n is the number of observations, P_i is the estimated ET_c by different models (predicted value), and O_i is the measured ET_a (the actual daily ET). Statistical analysis was conducted in R 3.4.2 and ET model were simulated using the Evapotranspiration package (Guo et al., 2016).

Results

Climate conditions and plant growth under different plant densities. Figure 1 shows the daily average climate data during the experimental period. The net radiation level was the highest in sunny days with the daily average value >80 W·m⁻². The net radiation in cloudy days was less than 50 W·m⁻². The corresponding ET_a was 2.7 mm·d⁻¹ on sunny days and 0.7 mm·d⁻¹ on cloudy days. RH varied from 65% to 95% during the experiment and tended to change in opposition to radiation and air

temperature. The corresponding RH is 75% on sunny days and 90% on cloudy days. Average daily air temperature varied from 21 to 29 °C. The corresponding daily air temperature was 25.7 °C in sunny days and 24.1 °C in cloudy days. As air temperature increases, air can hold more water, and RH decreases. ET is driven by VPD, which is a function of temperature and RH. As VPD increases, the plant transpires faster due to the larger difference in vapor pressures between the leaf and the air. There was a significant correlation between weather data and ET_a , indicated by the coincident occurrence of peaks and valleys (Fig. 1).

The Pearson correlation analysis was conducted to get a better understanding of the relationship between ET_a and climate data. As shown in Table 2, a positive correlation was found between ET_a and radiation/ PAR ($r > 0.9$, $P < 0.001$) and a negative correlation between ET_a and RH ($r = -0.77$, $P < 0.001$), whereas the correlation was not significant between ET_a and daily air temperature with $r = 0.46$ and $P > 0.05$.

The LAI in different tray size at harvest stage varied from 3.3 to 7.0. LAI increased with increasing density. As Fig. 2A shows, the 288-plug tray maintained the highest LAI throughout the entire period, whereas the 72-plug tray had the lowest due to the density difference. LAI of baby pakchoi in 288-plug tray reached 3.0 at 14 d after sowing (DAS), whereas LAI of the 72-plug tray reached 3.0 at 20 DAS. The LAI growth rate (compared with the day before) reached a peak value (206% for 72-plug tray and 160% for 288-plug tray) at 8 to 10 DAS (Fig. 2B). The first true leaf was expanded in 8 to 10 DAS compared with former stages, which made the peak value of LAI growth rate. After 10 DAS, the growth rate of LAI decreased. The increase rate of LAI at different densities showed a different trend from that of LAI

value. The highest increase rate occurred in 72-plug tray (Fig. 2B).

Determination of crop coefficient. According to FAO-56, K_c is mainly affected by the crop characteristics, agronomy, growth stages, and climate conditions. The frequency of rain or irrigation is important during the early growth stage. The K_c values can be classified into four stages: initial, crop development, midseason, and late season. In this research, the baby leaf grows only for the first three stages before harvest. The initial period represents the period with 10% groundcovered by crops, and the develop-

ment period extends from the end of the initial stage to the effective full cover (Allen et al., 1998). Midseason extends from effective full cover to when plants begin to decrease. The effective full cover can be predicted when the crop reaches a LAI of 3.0. For baby leafy vegetable, taking baby pakchoi as the example, the initial stage starts from sowing to the cotyledons fully expanded with coverage under 10%. In this stage, substrate surface evaporation contributes the most to the ET. The development starts from emergence of the first true leaf to full coverage with LAI = 3.0. These stages

are highly related to plant density and growth rate.

Soil evaporation in the initial stage contributes the most to crop water demand. Therefore, the impact of precipitation or irrigation needs to be considered when determining the $K_{c\text{ ini}}$ value. $K_{c\text{ ini}}$ is related to the ET_0 and interval between irrigations. As the irrigation frequency in greenhouse was twice per day, the substrate surface kept being wet. According to the relation curve of average $K_{c\text{ ini}}$ and ET_0 and the interval between irrigations >40 mm per event for medium and fine textured soils in FAO 56, when the ET_0 is <5 mm·d⁻¹ and the irrigation event occurs less than 1 d, the $K_{c\text{ ini}}$ value should be 1.15. The $K_{c\text{ mid}}$ is recommended as 1.05 for small vegetables at the full growth stage (with LAI >3.0) (Allen et al., 1998). Table 3 lists the growth stage and the LAI of different plant densities. The time interval was decided by LAI for each group. The K_c values of each stage under different plant densities are listed correspondingly.

Estimation of crop ET_c . By introducing K_c to the four evapotranspiration models, we obtained the predicted daily ET_c of the entire 17 d of experiment period (Fig. 3). During the experiment period, the fluctuation pattern of predicted ET_c was similar to the measured ET_a .

The FAO-PM and PT models had higher accuracies in predicting ET_c compared with the Radium and Penman models, which overestimated ET_c under most conditions (Fig. 3). The FAO-PM and PT models showed better performance on sunny day than cloudy days. Overestimates were found in cloudy day such as DAS of 6, 7, 10, and 11. MAPE, RMSE, R^2 , and AIC were calculated to indicate the performance of the four models in different plant densities (Table 4).

The overall performance showed that FAO-PM and PT models performed better than the other two models in different plant density groups. The performance of Penman model ranked the last. MAPE <50% was considered appropriate model performance. Hence, PT, FAO-PM in 200-plug tray group, and Radium in the first three groups (72-, 128-, and 200-plug trays) were acceptable. Models with smaller RSME represent better prediction of results. FAO-PM and PT models showed better results (RMSE = 0.4 to 0.6 mm·d⁻¹) than Radium and Penman models in four groups. Meanwhile, the FAO-PM and PT models had a higher R^2 value at ≈0.7 and lower AIC value than those of Radium and Penman in different plant density groups.

Discussion

ET is affected by variations in greenhouse environmental factors, and the order of correlation with ET_a is PAR > net radiation > humidity > VPD > air temperature. This result is consistent with those of Orgaz and Casanova, who also concluded that solar radiation was the main factor affecting ET (Casanova et al., 2009; Orgaz et al., 2005).

Fig. 1. Greenhouse climate factors and measured actual average daily evapotranspiration (ET_a). PAR = photosynthetically active radiation.

Table 2. Correlation analysis of climate factors with ET_a .

	ET_a	Radiation	PAR	Air temp	RH
ET_a	1	0.93	0.94	0.46	-0.77
Radiation	***	1	0.99	0.45	-0.79
PAR	***	***	1	0.42	-0.76
Air temperature				1	-0.62
RH	***	***	***	**	1

ET_a = actual evapotranspiration; PAR = photosynthetically active radiation; RH = relative humidity.

, *Significant at $P = 0.05$ or 0.01 , respectively.

Fig. 2. Dynamic of (A) leaf area index (LAI) and (B) LAI growth rate of baby pakchoi in different plant densities (72, 128, 200, and 288 plants/tray). Dashed line indicates the tray was fully covered by plant canopy. DAS = days after sowing.

Table 3. Crop coefficient (K_c) at different stages in this study.

Stages	K_c	72		128		200		288	
		DAS	LAI	DAS	LAI	DAS	LAI	DAS	LAI
Initial	1.15	0–7	<0.08	0–5	<0.11	0–5	<0.12	0–5	<0.18
Development	1.15–1.05 ²	8–19	0.08–3.0	6–17	0.11–3.0	6–15	0.12–3.0	6–13	0.18–3.0
Middle/full	1.05	20–25	>3.0	18–25	>3.0	16–25	>3.0	14–25	>3.0

²Crop coefficient during development stage was linear decreasing for 1.15 to 1.05.

LAI = leaf area index; DAS = means days after sowing.

Fig. 3. Comparison of different evapotranspiration (ET) models in predicting the daily crop ET (ET_c) vs. actual average daily ET (ET_a). Radsum = simplified radiation sum model; FAO-PM = FAO Penman-Monteith model; PT = Priestley-Taylor model.

Table 4. Evaluation of model performance under different plant densities.

Plants/tray	Model	MAPE (%)	RMSE (mm·d ⁻¹)	R ²	AIC
72	Radsum	46.33	0.7	0.52	-14.09
	Penman	73.80	0.8	0.31	-7.66
	FAO-PM	50.92	0.5	0.73	-23.83
	PT	51.75	0.5	0.75	-25.17
128	Radsum	42.55	0.6	0.64	-16.03
	Penman	70.48	0.8	0.44	-8.65
	FAO-PM	53.26	0.6	0.67	-17.45
	PT	52.22	0.6	0.69	-18.59
200	Radsum	43.80	0.7	0.55	-13.24
	Penman	70.42	0.8	0.37	-7.50
	FAO-PM	47.67	0.6	0.70	-19.97
	PT	48.79	0.6	0.71	-20.51
288	Radsum	59.49	0.7	0.58	-12.04
	Penman	89.71	0.8	0.41	-6.32
	FAO-PM	61.61	0.6	0.72	-18.99
	PT	64.82	0.6	0.73	-19.29

MAPE = mean absolute percentage error; RMSE = root mean squared error; AIC = Akaike information criterion; Radsum = simplified radiation sum model; FAO-PM = FAO Penman-Monteith model; PT = Priestley-Taylor model.

The dynamic change of LAI was significantly different among the four planting densities groups in our study, but the difference of measured ET_a was not statistically significant. Some studies reported that both K_c and ET_c were highly correlated with LAI (Netzer et al., 2009), and higher LAI increased ET as biomass development related to water use efficiency (Jha et al., 2018). In our study, the main reason that LAI had less effect on ET may be the short growth period of baby leaf having less impact of LAI on K_c . Also, the relatively high-frequency irrigation kept the substrate surface wet, and the evaporation from the surface of the substrate was

relatively higher than plant transpiration on the growth stage.

The predictions of the four models show that the Penman and Radsum models did not predict the actual evapotranspiration well. In contrast, FAO-PM and PT provided better predictions, with R^2 values of ≈ 0.7 . The Radsum model only considered the radiation as input, without humidity, for the ET prediction. In the case of extreme humidity conditions, the prediction results could be biased (Sentelhas et al., 2010).

The FAO-PM model, a function of net radiation and VPD, was less effective compared with the PT model, which agrees with

Sumner's observations (Sumner and Jacobs, 2005). The FAO-PM method would seriously underestimate the ET_0 in a greenhouse environment with small wind speed (Fernandez et al., 2010). In this research, the average wind speed above the plant canopy in greenhouse was $\approx 1 \text{ m·s}^{-1}$ with circulating-fan ventilation. Therefore, the FAO-PM model is applicable for the well-ventilated greenhouse. The Penman model mainly considers the energy balance and does not take into account the dynamic changes of plants, so the prediction accuracy was lower than FAO-PM. Compared with the FAO-PM model, the PT model had fewer parameters. It is more suitable for the conditions of the uniform wet ground surface, which fits the conditions of greenhouse used (Sumner and Jacobs, 2005). After adjustment by K_c , the PT model is recommended for the prediction of greenhouse evapotranspiration. These models can be used for daily irrigation scheduling by being implemented in a decision support system. The calibration of parameters such as crop resistances and α_{pt} (i.e., Priestly Taylor) may improve the prediction results (Villarreal-Guerrero et al., 2012).

Higher accuracy of FAO-PM and PT than Radsum and Penman demonstrating the importance of the VPD portion of these models (Prenger et al., 2002). With more comprehensive environmental variables, the models have better prediction efficiency. There are uncertainties associated with different models due to data and structure. A different model should be developed to minimize the biases in the further research.

Conclusion

In this study, four ET models were implemented in greenhouse baby pakchoi irrigation scheduling, and the performances of these models were evaluated. The ET_c (crop evapotranspiration) prediction results proved that the FAO-PM and PT models performed better than the Penman and Radsum models in greenhouse. This model-based precision irrigation scheduling portends to be meaningful in a decision support system to guarantee the water requirements of greenhouse baby pakchoi tray production.

Literature Cited

- Akaike, H. 1974. A new look at the statistical model identification. ITAC 19:716–723, doi: 10.1109/TAC.1974.1100705.
- Allen, R.G., L.S. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. FAO, Rome 300:D05109.

- Anlauf, R., P. Rehmann, and H. Schacht. 2012. Simulation of water uptake and redistribution in growing media during ebb-and-flow irrigation. *J. Hort. For.* 4:8–21, doi: 10.5897/JHF11.058.
- Campbell, G.S. and J.M. Norman. 2000. An introduction to environmental biophysics. Springer, New York.
- Casanova, M., I. Messing, A. Joel, and A. Canete. 2009. Methods to estimate lettuce evapotranspiration in greenhouse conditions in the central zone of Chile. *Chil. J. Agr. Res.* 69:60–70, doi: 10.4067/S0718-58392009000100008.
- Danfeng, H., S. Leiling, and Z. Kai. 2013. Primary study on pakchoi factory. *Acta Hort.* 79–84, doi: 10.17660/ActaHortic.2013.1004.7.
- Eitzinger, J., N. Schahbazian, I. Allahdadi, and G. Akbari. 2007. A decision support system for the optimization irrigation scheduling. *Pakistan J. Water Resources* 11:1–18.
- Fernandez, M.D., 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. *Irr. Sci.* 28:497–509, doi: 10.1007/s00271-010-0210-z.
- Guo, J., L. Juan, L. Chang, J. Zhang, and D. Huang. 2017. Discrimination of plant root zone water status in greenhouse production based on phenotyping and machine learning techniques. *Sci. Rep.* 7:8303, doi: 10.1038/s41598-017-08235-z.
- Guo, D.L., S. Westra, and H.R. Maier. 2016. An R package for modelling actual, potential and reference evapotranspiration. *Environ. Model. Softw.* 78:216–224, doi: 10.1016/j.envsoft.2015.12.019.
- Ilahi, W.F.F. 2009. Evapotranspiration models in greenhouse. Wageningen University, Netherlands, M.Sc.
- Jha, P.K., S.N. Kumar, and A.V.M. Ines. 2018. Responses of soybean to water stress and supplemental irrigation in upper Indo-Gangetic plain: Field experiment and modeling approach. *Field Crops Res.* 219:76–86, doi: 10.1016/j.fcr.2018.01.029.
- Jones, H.G. 2004. Irrigation scheduling: Advantages and pitfalls of plant-based methods. *J. Expt. Bot.* 55:2427–2436, doi: 10.1093/jxb/erh213.
- Jun, L.I., Y.P. Yao, W.H. Luo, J.F. Dai, H.U. Ning, X.U. Rui, X.B. Han, and H.J. Zhang. 2009. Transpiration of *Brassica chinensis* L. in a plastic greenhouse covered with insect-proof nets in lower reaches of Yangtze River: A simulation study. *Chinese J. Appl. Ecol.* 20:2241–2248.
- Karaca, C., A. Tezcan, K. Buyuktas, D. Buyuktas, and R. Bastug. 2018. Equations developed to estimate evapotranspiration in greenhouses. *Yüz. Yıl Üniv. Tarım Bilim. Derg.* 28:482–489, doi: 10.29133/yyutbd.427115.
- Kroggel, M., W. Lovichit, C. Kubota, and C. Thomson. 2012. Greenhouse baby leaf production of lettuce and komatsuna in semi-arid climate: Seasonal effects on yield and quality. *Acta Hort.* 952:827–834.
- Netzer, Y., C. Yao, M. Shenker, B.-A. Bravdo, and A. Schwartz. 2009. Water use and the development of seasonal crop coefficients for Superior Seedless grapevines trained to an open-gable trellis system. *Irr. Sci.* 27:109–120, doi: 10.1007/s00271-008-0124-1.
- Orgaz, F., M.D. Fernandez, S. Bonachela, M. Gallardo, and E. Fereres. 2005. Evapotranspiration of horticultural crops in an unheated plastic greenhouse. *Agr. Water Mgt.* 72:81–96, doi: 10.1016/j.agwat.2004.09.010.
- Penman, H.L. and B.A. Keen. 1948. Natural evaporation from open water, bare soil and grass. *Proc. R. Soc. Lond. A Math. Phys. Sci.* 193:120–145, doi: 10.1098/rspa.1948.0037.
- Prenger, J.J., R.P. Fynn, and R.C. Hansen. 2002. A comparison of four evapotranspiration models in a greenhouse environment. *Trans. ASAE* 45:1779, doi: 10.13031/2013.11429.
- Priestley, C. and R. Taylor. 1972. On the assessment of surface heat flux and evaporation using large-scale parameters. *MWRv* 100:81–92.
- Schneider, C.A., W.S. Rasband, and K.W. Eliceiri. 2012. NIH Image to ImageJ: 25 years of image analysis. *Nat. Methods* 9:671–675, doi: 10.1038/nmeth.2089.
- Sentelhas, P.C., T.J. Gillespie, and E.A. Santos. 2010. Evaluation of FAO Penman-Monteith and alternative methods for estimating reference evapotranspiration with missing data in Southern Ontario, Canada. *Agr. Water Mgt.* 97:635–644, doi: 10.1016/j.agwat.2009.12.001.
- Sumner, D.M. and J.M. Jacobs. 2005. Utility of Penman-Monteith, Priestley-Taylor, reference evapotranspiration, and pan evaporation methods to estimate pasture evapotranspiration. *JHyd* 308:81–104, doi: 10.1016/j.jhydrol.2004.10.023.
- Valdés-Gómez, H., S. Ortega-Farías, and M. Argote. 2009. Evaluation of the water requirements for a greenhouse tomato crop using the Priestley-Taylor method. *Chil. J. Agr. Res.* 69:3–11, doi: 10.4067/s0718-58392009000100001.
- Villarreal-Guerrero, F., M. Kacira, E. Fitz-Rodriguez, 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 Hort.* 134:210–221, doi: 10.1016/j.scienta.2011.10.016.
- Waller, P. and M. Yitayew. 2016. Evapotranspiration, p. 67–87. In: *Irrigation and drainage engineering*. Springer International Publishing, Cham.
- Xue, L., M. Hanping, Z. Zhiyu, Z. Xiaodong, and F. Weiguo. 2008. Experimental study on prediction of turf transpiration in greenhouse. *Agricultural Mechanization Res.* 12:119–121, doi: 10.3969/j.issn.1003-188X.2008.12.037.
- Yang, L.Q., X. Yang, H. Zhao, D.F. Huang, and D.Q. Tang. 2018. Ebb-and-flow subirrigation strategies increase biomass and nutrient contents and reduce nitrate levels in lettuce. *HortScience* 53:1056–1061, doi: 10.21273/Hortsci13065-18.
- Yuan, B.-Z., Y. Kang, and S. Nishiyama. 2001. Drip irrigation scheduling for tomatoes in unheated greenhouses. *Irr. Sci.* 20:149–154, doi: 10.1007/s002710100039.
- Zeng, C., X. Yang, C. Fan, and M. Wu. 2015. Preliminary study on characteristics of water evaporation of floating seedling greenhouse. *Chinese Agr. Sci. Bul.* 31:262–266.