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Estimating fan and pad greenhouse reference evapotranspiration using FAO-56 - Penman-Monteith and a simplified heat transfer approach for predicting internal temperature

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ABSTRACT

The recent increase in off-season crop cultivation in greenhouses requires prediction of crop reference evapotranspiration (ETo) to quantify size of irrigation equipments and water scheduling. Currently, estimating the reference crop evapotranspiration for a greenhouse crop is based on the FAO-56 Penman-Monteith formula which requires large set of external greenhouse input climatic data that is not usually available. Moreover, the prediction of ETo is difficult because the wind speed inside a greenhouse is low or approximate zero and the external greenhouses climate data differ markedly from inner greenhouse data. In order to calculate ETo from inside greenhouse a Penman-Monteith modified and simplified procedure was proposed as main objective of this study. The procedure is based on two steps that are to use the heat transfer approach to predict inside the greenhouses temperature, and secondly to employ the predicted temperature data to estimate ETo as suggested by FAO – irrigation and drainage paper 56. However, the relative humidity and radiation are to be estimated from data on temperature differences. The model was validated using meteorological data measured within Quonset type (20 × 9 × 3) greenhouse in Shambat - Khartoum North area in 2022. Prediction of temperature by heat transfer model was verified with greenhouse data reported by Hadi and Ahmad (2019). The model statistical verification shows that the fitted value of the model agreed with the calculated value by the formulas. The model was applied with data collected in nine houses located in three sites in Khartoum North for three seasons. The results indicated the possibility of using the proposed procedure to predict ETo for design and operation purposes for erecting new greenhouse in a new area because less meteorological factors are needed.

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***Keywords*:** Greenhouse, heat transfer, reference crop evapotranspiration, simulation, energy, heat, transfer

1. INTRODUCTION

As a kind of off- season cultivation, vegetables that are planted in greenhouses are capable of making full use of light, temperature, and other meteorological elements for plant growth; therefore, greenhouses not only solve the shortage of slack season vegetables, but conserve irrigation water in areas with limited water resources. Greenhouses have a special environment that supports the growth of crops, unlike in open fields where the water requirement varies greatly. Extensive research on prediction of indoor greenhouse ETo has been conducted. Katsoulas et al. (2001) summarized the study progress of soil moisture and heat transport in greenhouses. Katsoulas et al. (2019) investigated the effect of greenhouse moisture on canopy conductance of crop evapotranspiration. Ikhlas Ghiat et al (2021) reviewed evapotranspiration measurement models, techniques and methods for open and closed agricultural field applications. In addition, Cecilia Stanghellini et al. (2019) analyzed the radiation effects on transpiration of greenhouse crops. Moreover, leaf stomatal conductance simulated crop evapotranspiration in a greenhouse based on the mechanism model of leaf stomatal conductance and the computational fluid dynamics model, respectively. This research works primarily estimated the evapotranspiration of greenhouse crops from its physiological mechanism.

However, these methods that predict crop evapotranspiration (ETo) and depends on measuring the physiological parameters of greenhouse crops, are not suitable for design and operation of irrigation system in new area. Alternative methods that widely used are those using volume balance approach and outdoor climate variables (Liu et al., 2015). Prediction of ETo on using outside the greenhouse climate data results on overestimation of ETo (Hadi and Ahmad (2019), and constrained by unavailability of most of the important input parameters (temperature, relative humidity and radiation) (Hadi and Ahmad (2019). Bartzanas. and Kittas (2005) studied heat and mass transfer in a large evaporative cooled greenhouse equipped with a progressive shading. Their experimental results showed strong climate heterogeneity along the air stream from cooling pads to extracting fans. For solving this problem Allen et al (1998) recommended employing limited data procedure that depends on greenhouse temperature only.

This requires using a scheme for prediction of indoor greenhouse temperature. As a response to this situation some equations based on temperature are recommended. These include Hargreaves equation (Hargreaves and Allen 2003; Shahidian et al. 2012), the simplified energy balance approach (Liu et al. 2015), linear regression (Perugu et al. 2013), weather forecasts (Lorite et al. 2015), and atmometers (Jaafar and Ahmad 2018). Although the Hargreaves equation requires local calibration because it over estimate ETo in humid climates (Trajkovic 2007), its use in semiarid climates around the world is well documented (Allen et al.1998; Hargreaves and Allen 2003; Martınez-Cob and Tejero Juste 2004; Samani 2000; Shahidian et al. 2012; Jensen and. Wright, 1978).

These temperature based equations are criticized to be empirical in nature and site specific (Fazlil-Ilahi 2009). Local calibration of such equations is sometimes cumbersome, and more research is required in other areas in order to define how weather variables can be used to derive reference evapotranspiration within greenhouses.

Greenhouses can be naturally or fan and pad ventilated, and these aerodynamic conditions affect crop water requirements. However, little research has focused on the variation of ETo with aerodynamic conditions within greenhouses (ventilated or unventilated). Many greenhouses in developing countries are only naturally ventilated, especially in winter, and estimates of ETo in such conditions are a prerequisite to any efficient water management strategy. Kittas et. al, (2005) considered the ventilated greenhouse as a heat exchanger, the fans located on the wall opposite to the pads create a longitudinal fresh air flow through the greenhouse due to solar radiation incident on the canopy and the soil. They showed that heat losses through the cover o the outside limit this warming process, and for simplicity, the fraction of the incident solar radiation responsible for sensible heat transfer could be assumed to be fixed and equal to (1- α), where α is the fraction responsible for evapotranspiration. The heat balance, for a differential increment along the airflow, gave an equation for the internal greenhouse air temperature.

The difference between internal and external evapotranspiration varies according to meteorological conditions. Usually, evapotranspiration inside a greenhouse is around 60 to 80% of that verified outside (Montero et al., 1985; Rosenberg et al., 1989). Farias et al. (1994) observed that the reference evapotranspiration (Eto) inside greenhouses was always lower, ranging on 45 to 77% of that verified outside. Braga & Klar (2000) observed that the values of reference evapotranspiration were 85 and 80% of the reference evapotranspiration rate. Reference evapotranspiration can be measured by several methods, and the class A pan method has been one of the most utilized methods worldwide because of its simplicity, relatively low cost, and yielding of daily evapotranspiration estimates. Greater precision, however, can be obtained when it is utilized for periods of at least five days (Marouelli et al., 1996). Its use inside greenhouses is still object of controversy. Research results about what pan coefficient Kp) should be utilized inside the greenhouse are not conclusive. In addition, some producers consider leaving an unproductive area of approximately 10 m^2 occupied by the class A pan inside the greenhouse not viable. Alternative methods have been sought to estimate ETo inside greenhouses. Among them, the reduced-size pan and the atmometer deserve special attention. Therefore the objective of this study is develop and test a procedure to estimate ETo inside greenhouse depending on simulated temperature using heat transfer and the FAO-56 procedure using limited data.

2. MATERIALS AND METHODS

2. 1. Experimental site and Design

The experiments were conducted at Khartoum North-Sudan (15.40 N Latitude, 32.32 E Longitudes and altitude 380 m above "msl") at three sites (El Alafoon, Halfaya, and Shambat) during the period from Jun to October 2020 (first season) and July to October 2021 (second season) under controlled environment greenhouse. The specifications of each house includes, a galvanized frames (38 × 8.5 × 2.5 m), double layers of polyethylene cover fan and pad cooling system, drip irrigation system (Pipe with 3/4 in diameter and 35 m length, nozzles 50 cm apart and water sump with a pump). The instruments used for measuring climate variables were installed inside and outside each house, and measurements were made in triplicate. They include a class A - pan, for direct measurement of ETo, Air temperature (Tmax, Tmin) and relative humidity were measured by means of a Campbell Scientific CS-215 combined probe with radiation shield. A Met-One 034B Windset anemometer was used to measure wind speed. Solar radiation was measured using a CS300 Apogee pyranometer manufactured by Campbell Scientific Irmak et al. (2005). A class A pan, were installed in the center of the greenhouse. The class A pan was constructed of nr. 22 galvanized iron sheet, 1.21 m in diameter and 0.255 m in depth. The pans were installed on a wooden pallet 0.15 m from soil surface. Another class A pan, were installed outside the greenhouse to measure ETo outdoor using PM method.

The experimental works were arranged in a completely randomized design (CRD) with three replicates to collect inside and outside greenhouse environmental factors: temperature, relative humidity and air velocity. The measurements inside the greenhouse were made at three locations at one meter distance from the pad, at the middle of the greenhouse and at one meter distance from the fans. Data collected to assess the model capability to predict internal temperature and to estimate ETo with minimum data.

2. 2. Heat and mass balance to predict indoor temperature

Heat loss from a greenhouse usually occurs by all three modes of heat transfer: conduction, convection and radiation. Usually many types of heat exchange occur simultaneously. The heat demand for a greenhouse is normally calculated by combining all three losses as a coefficient in a heat loss equation. In this model the calculation of the inner temperature depends on estimating the various forms of the heat loss in greenhouses.

The calculation steps include:

i) Heat transfer through surface area: The surface area (A) is calculated following Hadi and Ahmad (2019) as:

$$A = 0.5*(2\pi DL+2\ \pi D)$$

where: A = Area of the greenhouse (m^2); D = house height (m); π = Constant = 3.14; L = house Length (m)

ii) Rate of heat transfer by conduction (Q):

$$Q = (T_o - T_i)/RT$$

where: Q = Rate of heat transfer by conduction (W)' To = Outside air temperature (°C)' Ti = inside air temperature (°C); RT = Total thermal resistance of the greenhouse wall (°C /W).

iii) Heat balance:

$$RT = R_1 + R_2 + R_3$$

where: R1 = Thermal resistance of outside film (R_1= 1/ (h_o * A); R_2 = Thermal resistance of wall material R2 = x / (K A); R_3= Thermal resistance of inside air film R_3 = 1 / (h_1 * A).

Values of ho and h1 were obtained from literature and taken as 33.3333 Wm^2.°C and 8.3333 Wm^2. °C respectively. The value of the thermal conductivity of the plastic film was obtained from James (1983) and Hadi and Ahmad (2019) to take a value of 0.0404 Wm^2 °C.

iv) System efficiency

$$Eff = (t_{oa} - t_{hm}) / (t_{oa} - t_{wb})$$

where: t_{oa} = Outside air dry bulb temperature °C;
t_{hm} = greenhouse overall mean temperature (°C)'
t_{wb} = Outside wet bulb temperature (°C).

Assume initial temperature (T_i) to be equal to t_{hm} and iterate till Eff is >75% to reach acceptable T_i to be taken for the second step to predict ETo with only this temperature data.

2. 3. Theory of limited data procedure

2. 3. 1. Input data

The monthly average outdoor greenhouse maximum, minimum temperature, in degrees Celsius (°C) and site characteristics (Latitude and altitude). For estimation of wind speed ether input the wind speed from local station in the range of 2 to 0.5 m/s or just use 2 m/s due to the small crop height (0.15 m) and reduced speed frequently encountered inside the greenhouse.

Taking the Location input data (altitude (z), and latitude) the associated intermediate parameters estimated from maximum, and minimum temperatures are depicted in the flow chart of Figure 1 and detailed by utilizing the following relations (Allen et al. 1998; Allen 2005). Average temperature, T(°C) = $(T_{max} + T_{min})/2$;

i) **Estimating Wind speed:** The calculation procedure require to adjust wind speed to the standard height of 2 m.

ii) **Estimating Missing Vapor Pressure Data:** An estimate of actual vapor pressure is proposed to be made by assuming minimum air temperature is equal to dew point temperature Jensen et al. (1990). If T_{min} is used to represent T_{dew} then

$$V_P (T_{min}) = 0.611 \exp [(17.27 * T_{min}) / (T_{min} + 237.3)]$$

where $V_P (T_{min})$ = actual vapor pressure obtained from minimum air temperature (kPa)
Slope of the saturation vapor pressure versus temperature curve,

$$D = 2503 \exp ((17.27*T)/(T_{min} + 237.3)) /(T_{min}+ 237.3)^2;$$

Latent heat of vaporization of water, k, = $2.501 - (2.361x\ 10^{-3})*T$;
Psychometric constant, c = 0.000665*P;
Actual vapour pressure, ea = $0.611 \exp (17.27*T/(T_{min} + 237.3))/(T_{min} + 237.3)$;
Saturation vapour pressure:

$$es = 0.611 (\exp (17.27*T/(T_{max} + 237.3)) + \exp (17.271T_{min} /T_{min} + 237.3);$$

iii) **Estimating Missing Radiation Data:** solar radiation is often estimated from sunshine data using Angstrom equation:

$$Rs = (0.25+ 0.5* (n/N)) * Ra$$

where: Rs = solar radiation (MJm^{-2} day −1); n = sunshine hours (h /day); N = daylight hours (h /day); Ra = extraterrestrial radiation (MJm $^{-2}$/ day). Extraterrestrial radiation and daylight hours are computed as a function of the local latitude and Julian data (Allen et al. 1998, Cai et al. 2014).
Extraterrestrial radiation,

$$Ra = (24 \times 60/\pi)*Gsc * dr*[\omega s \sin(\varphi) \mathrm{Sin}(\sigma) + \mathrm{Cos}(\varphi) \mathrm{Sin}(\sigma)]$$

where: Ra = extraterrestrial radiation [MJ m^{-2} day^{-1}], Gsc = solar constant = 0.0820 MJ min^{-1}. Dr = inverse relative distance Earth-Sun (rad), S = sunset hour angle (Equation 25 or 26) [rad], Φ = latitude [rad], Ϭ = solar declination [rad]. Solar radiation, Rs, = $0.16*Ra*(T_{max} - T_{min})^{0.5}$;
Clear sky radiation, Rso = (0.75 + 2 x 10^{-5})*Z) Ra, Where z = altitude above sea level (m);
Net long wave radiation, Rnl = $\sigma*(((((T_{max}+273.16)^4) + (273.16+T_{min})^4)/2)*(0.34-0.14 *(ea^{0.5}))*((1/35/Rso) - 0.35))$; Net shortwave radiation, Rns = 0.77*Rs' and Net radiation, Rn = Rns – Rnl; Finally, apply the following FAO -56- PM equation using the above parameters to predict ETo (Allen et al 1998):

$$ETo = (0.408*(Ra-G) + \Upsilon(900/(T+273))*u_2*(es - es))/(\Delta+\Upsilon(1+0.34U_2))$$

where: ETo is the reference evapotranspiration (mm day); Rn is the net radiation at the crop surface (MJ m), which was estimated according to the procedures outlined by Allen et al (1998) and Pandey and Pandey (2016**)**; G is the soil heat-flux density (MJ m^2/day). ETo calculations were made using measured climate variable inside and outside each greenhouse.

iv) **Statistical analysis:** To evaluate the performance of the proposed model four different statistical indices were used. Comparisons for each equation were made between daily reference evapotranspiration values and daily values calculated using the FAO56-PM method and ETo measured by evaporation pan. FAO56-PM was selected as a benchmark method for comparison, taking into account that it is a globally accepted method which is used under a variety of climatic regimes and reference conditions. Such reference equation is authenticated by its comparison with ETo values measured directly by the evaporation pan.

A. Four indices usually recommended to be used to compare model predicted (P) and observed (O) variables is employed (Willmott, 1982) and they include:

1) The "Index of Agreement" (d): The "Index of Agreement" (d) is alternatively proposed as a descriptive measure which can be applied in order to make a cross-comparison between the models, and both relative and bounded measure are recommends

$$d = 1 - \frac{\sum_{i=1}^{N}(P_i - O_i)^2}{\sum_{i=1}^{N}(|P_i'| + |O_i'|)^2}, \quad 0 \le d \le 1$$

where: O_i stands for observed values (estimated by FAO56-PM) and P_i stands for values predicted by the compared methods $P = a\ O_i + b$, $P_i' = P_i - O$.

2) The mean bias error (MBE) which describes the bias, the variance of the distribution of differences (Sd^2) Willmott, 1982):

$$MBE = N^{-1} \cdot \sum_{i=1}^{N} (P_i - O_i)$$

3) The root mean square error (RMSE): summarize the mean difference between observed and predicted values. RMSE is practical as it shows the errors in the same unit and scale as the parameter it shelf, The RMSE can range from zero to infinity with the lower values being the better (values preferably close to 0).
   The root mean square error (RMSE)

$$RMSE = \left[N^{-1} \cdot \sum_{i=1}^{N} (P_i - O_i)^2 \right]^{0,5}$$

4) The variance of the distribution of differences (sd^2): It expresses the variability of the difference between predicted (P_i) and observed (O_i) values

$$s_d^{\,2} = (N-1)^{-1} \cdot \sum_{i=1}^{N} (P_i - O_i - MBE)^2$$

B. Analysis of variance using complete randomized design is used taking ETo estimated by class -A- pan as a reference case study and also ETo determine by PM-56- using inside greenhouse climate data as a second case study. The latter is chosen for its practicability and reduced costs.

3. RESULTS AND DISCUSSIONS

3. 1. Eto on basis of direct measurement by inside evaporation pan

Table 1 shows values of ETo obtained by four prediction techniques (Simulated Temp and limited data, limited outside temperature data, correction of ETo measured from outside climate data, and pan measurement). It is evident from the table that ETo values inside the greenhouse are lower than outdoor This is in agreement with (Farias et al., 1994; Martins et al., 1994; Braga and Klar, 2000), who attributed this phenomena to the influence of the main factors of evaporative demand of the atmosphere (such as lower wind speed values, higher relative humidity and lower incidence of direct sun rays). Table 1: Average ETo determined by four techniques (Simulated Temp and limited data, limited outside temperature data, correction of ETo measured from outside climate data, and pan measurement). Figure 1 shows average values of ETo by using the different techniques. In reality they all follow similar trend. It is evident from analysis of the randomized block design used there is no significant differences in amount of ETo measured by the various four techniques and in the expected error at 1% and 5% level of probability. Upon using test of least significant difference (LSD) there is no significant differences in predicting ETo by method of simulated temperature and limited data or by using method of limited outside data with PM equation, or by method of correcting PM with historical outside climate data compared to direct measurements using evaporation pan.

Table 1. Average ETo determined by four techniques

Replication	Eto in from Simulated Temp and limited data	Eto In from Limited outside data PM	Eto In from correcting PM outside data	Eto from In Pan
R1 = Year 1-Moth1	4.11	4.74	5.15	5.27
R2 = Year 1-Moth 2	4.09	4.25	4.67	4.96
R3 = Year 1-Moth 3	4.15	3.85	4.38	4.14
R4 = Year 2 -Moth1	4.23	4.40	5.51	4.69
R5 = Year 2 -Moth 2	4.13	3.56	5.03	3.92
R6 = Year 2 -Moth 3	4.07	4.10	4.80	4.58
R7 = Year 3 -Moth1	3.87	3.66	5.28	3.60
R8 = Year 3 -Moth 2	3.84	4.48	5.11	3.93
R9 = Year 3 -Moth 3	3.95	3.94	4.79	4.41
Mean	4.05	4.11	4.97	4.39

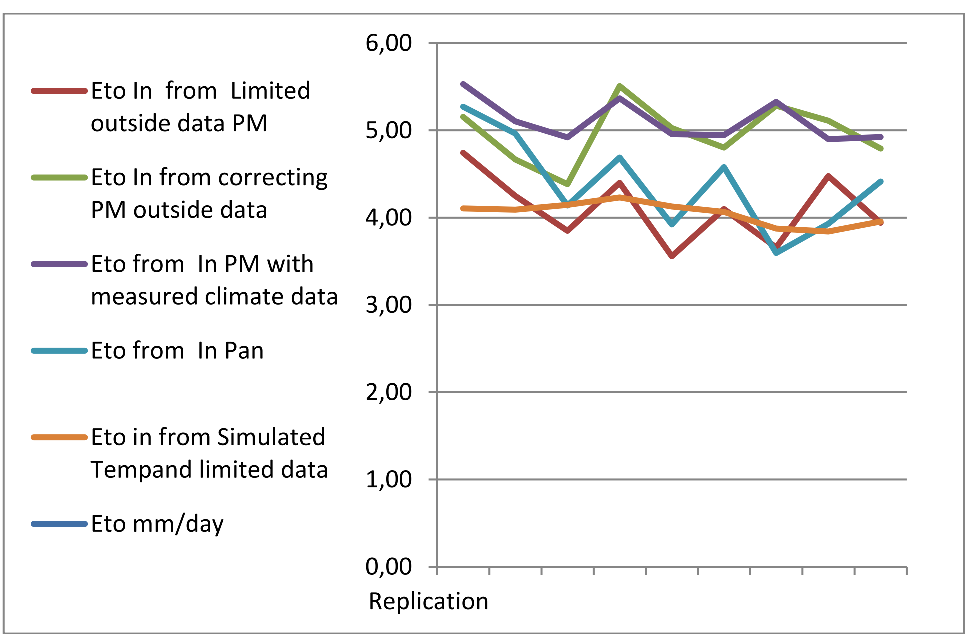

Figure 1. Average values of ETo by using the different techniques

Table 2 gives the evaluation indicators to assess the predictability of each of the suggested method to estimate ETo. The table confirms that there is no significant differences between the tested methods and any one of them can do the job satisfactory. This is evident by the low coefficients obtained with all methods with all indicators.

Table 2. Performance of the four ETo prediction techniques with respect to statistical indices jugged according to ETo measured by evaporation pan.

Replication	Eto in from Simulated Temp. and limited data	Eto in from Limited outside data PM	Eto In from correcting PM outside data	Eto from in PM with measured climate data	Eto from Inside Pan
Average Eto (mm/day)	4.05	4.11	4.97	5.11	4.39
d = Index of Agreement	0.000	0.00	0.00	0.00	0.00
MBE= mean bias error	-1.06	-1.00	-0.14	0.00	0.00
RMSE = The root mean square error	0.36	0.35	0.10	0.00	0.00
Sd^2 = variance distribution of differences	0.06	0.13	1.02	0.00	0.00

3. 2. Methods for estimating ETo related to estimation by PM and indoor climate variables

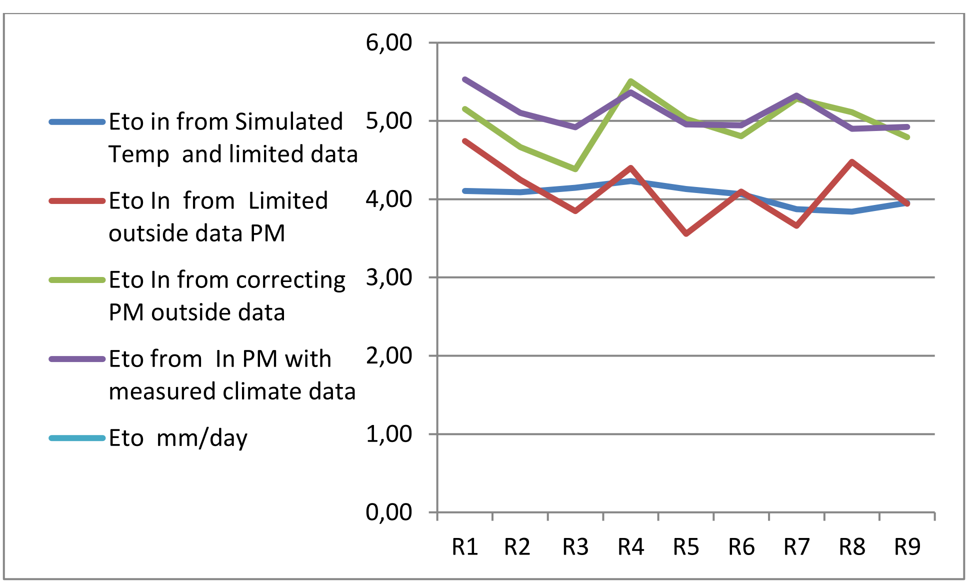

Figure 2. Performance of four ETo prediction technique related to using PM method with whole range of climate data

Using analysis of variance there is no significant differences in values of ETo predicted by any of the tested four treatments and their expected error. This result is confirmed by Figure 2 and data of Table 3. Table 3 indicate that all evaluation indicators (Index of agreement, mean bias error, the root mean square error, and variance of the distribution of differences) the obtained coefficients are low indicating for all cases no significant differences between the four techniques in comparison with PM and indoor climate variables

The results of the least significant test given in Table 3 confirm by the low coefficients obtained with each ETo prediction method there is significant differences between these techniques.

Table 3. Test of Lest Significance Difference (LSD) of the three ETo prediction methods in relation to estimation by PM and inner climate data

Treatment	d = Index of Agreement	MBE = mean bias error	RMSE = The root mean square error	Sd^2 = variance of the distribution of differences
Eto in from Simulated Tempand limited data	0.000	-1.059	0.361	0.059
Eto in from Limited outside data PM	0.000	-1.000	0.352	0.133
Eto in from correcting PM outside data	0.000	-0.139	0.095	1.023
Eto from in PM with measured climate data	0.000	0.000	0.000	0.000

4. COCLUSIONS

The statistical verification of the develop ETo using heat transfer module to predict indoor greenhouse temperature and the module of the simplified method shows that the fitted values of the model agreed with the calculated values by the formulas. The results indicated the possibility of using the proposed procedure to predict ETo for design and operation purposes for erecting new greenhouse in a new area because less meteorological factors are involved.

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