Overview of modelling techniques for greenhouse microclimate environment and evapotranspiration

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Abstract: Domestication of plants by man through greenhouse crop production has revolutionized agricultural farming systems worldwide. Selecting the appropriate greenhouse technology together with the user-friendly evapotranspiration (ET_c) model can optimize crop water use. The greenhouse microclimate environment has nearly zero wind speed and low radiation, hence low transpiration due to high temperature and humidity. Therefore, matching the greenhouse microclimate with the appropriate ET_c model will certainly optimize crop water use efficiency since water is becoming a scarce resource globally, more so in the greenhouse environment. This is one of the main reasons why the gap between the dissemination of various advanced ET_c models and the application by the greenhouse crop producers' community needs to be bridged. The likelihood or chances of rapidly disseminating and adopting advances in ET_c estimating technology by a larger greenhouse crop producers community will increase if greenhouse ET_c models become more user-friendly and available. The contribution of the greenhouse system to increased and sustainable food production must come through improved disseminating, adopting and use of existing greenhouse ET_c models. FAO recommends a standard approach for the determination of crop water requirements utilizing the product of reference evapotranspiration (ET_0) and crop coefficient (K_c) values. The FAO approach can also be used in greenhouse cultivation systems. However, studies connecting greenhouse technologies and methodologies for measuring ET_0 or ET_c in greenhouses are not available. There are also few studies undertaken that compared the performance of ET_0 or ET_c models under different categories of greenhouse conditions. In this review, a link between greenhouse technology and ET_0 model or ET_c model, and how existing knowledge and methodologies in ET_0 or ET_c measurements can actually enhance the sustainability of greenhouse farming have been highlighted. The categories of greenhouses, equipment commonly used, and the data collected for ET_0 and ET_c measurements have been established in the article. This review aimed to evaluate and summarize ET_0 and ET_c models currently available and being used in the various greenhouse categories. The accuracy assessment levels of the ET_0 models about the category of the greenhouse microclimate environment were carried out.

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1 Introduction

Globally, the greenhouse farming system has become a highly industrialized phenomenon with partially or fully controlled growing conditions. The growing conditions are computer-controlled or otherwise and are made suitable for optimum crop production with maximum economic and profit margins[1]. Thus, creating a means for sustainable crop intensification can lead to optimization of water-use efficiency in an environment of water scarcity in addition to better control of product quality and safety[2].

Greenhouse cultivation systems, regardless of geographic location, comprise fundamental climate control components. Depending on the design and complexity, these climate control components provide more or less climate control and conditions to a varying degree of plant growth and productivity. Various greenhouse microclimate models with many state variables (heating, energy storage, ventilation, fogging) have been reported. Many studies on crop water requirements in the greenhouse microclimatic environment have also been reported, notable among them are water consumption for tomatoes in the Netherlands[3,4], Mediterranean regions[5,6], and Thailand[7]. A number of studies

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have evaluated evapotranspiration (ET_c) models at all levels from a single leaf to the whole canopy in both vegetables[8-12] and ornamental crops[13,14] growing in greenhouses. However, these ET_c models have not been linked to the state-of-the-art level of technologies and microclimate conditions in the greenhouses. Selecting the appropriate greenhouse technology together with the user-friendly ET_c model can optimize crop water use. Researchers and journal authors alike, simply, do not often provide detailed information about the technology level of greenhouses in which the study was done. At best, they mention the type of instruments and geographical location of the greenhouse without further details about the technological category of the greenhouse. This information, if available, may give a clue as to which irrigation schedule to adopt. Thus, the greenhouse farmers have no better choice left than to do “trial and error” irrigation based on local experience that usually results in water waste despite water scarcity in the greenhouse. This review is intended to evaluate the link between prevalent greenhouse microclimate conditions and associated technology levels with the existing ET_c models in the greenhouse for sustainable intensification of greenhouse agriculture.

2 Greenhouse microclimatic environment and meteorological data

2.1 Greenhouse microclimatic environment

Greenhouse technologies available currently show that it is possible to cultivate all horticultural species in any region of the world, provided the greenhouse is properly designed and equipped to control the climatic parameters which is a key to agronomic practices. However, for profitable and sustainable cultivation of the target crop, a much stricter selection of the region is necessary based on the climatic conditions and the requirements of the selected horticultural crop[15]. Site selection is a key factor for profitable and sustainable greenhouse crop production. Main factors determining location and site selection of a greenhouse production area, according to Nelson[16], and Castilla et al.[17], are the cost of production, quality produced yield, and transportation cost to markets. Obviously, the cost and quality of production depend on the local climate and the greenhouse microclimate.

Air temperature, solar radiation and relative humidity are among the most important variables of the greenhouse climate that can be controlled. Air temperature does conditions not only crop development and production but also energy requirements which account for up to 40% of the total production costs in the greenhouse. Humidity, traditionally expressed in terms of relative humidity is another important variable. Relative humidity within the range of 60%-90% has little effect on plants. Values below 60% may occur during ventilation in arid climates, or when plants are young with small leaves, and this can cause water stress. Serious problems can occur if relative humidity exceeds 95% for longer periods, particularly at night as this favors the rapid development of fungal diseases such as *Botrytis cinerea*[18]. Removal of the heat load is the major concern for greenhouse climate management in arid and semi-arid climate conditions. This can be achieved by reducing incoming solar radiation; removing extra heat through air exchange; increasing the fraction of energy partitioned into latent heat. Shade screens and whitewash are the principal measures taken to reduce incoming solar radiation. Greenhouse ventilation is an effective way to remove extra heat through air exchange between the inside and outside (when the outside air temperature is lower); evaporative cooling is the common technique for reducing sensible heat load by increasing the latent heat fraction of dissipated energy[18,19].

High summer temperatures mean that heat must constantly be removed from the greenhouse. A simple effective way of reducing the difference between inside and outside air temperatures is to improve ventilation. Natural or passive ventilation requires very little external energy. If the greenhouse is equipped with ventilation openings both near the ground and at the roof, hot internal air is replaced by the cooler external air during hot sunny days when there is a slight wind. The external cool air enters the greenhouse through the lower side openings while the hot internal air exits through the roof openings due to the density difference between air masses of different temperatures; the result is a lowering of the greenhouse temperature. Sufficient ventilation is a key to optimal plant growth, particularly in cases of high outside temperatures and solar radiations which are common prevailing conditions during the summer in Mediterranean regions of the world. For the variables determining greenhouse air temperature and the necessary temperature control measurements to be known, a simplified version of the greenhouse energy balance equation was as follows[20]:

$$V_a = \frac{0.0003\tau R_{s,o-\max}}{\Delta T} \tag{1}$$

where, V_a is the ratio Q/Ag; Q is the ventilation flow rate,(m^3/s; Ag is the greenhouse ground surface area, m^2; τ is the greenhouse transmission coefficient to solar radiation; $R_{s,o\text{-max}}$ is the maximum outside solar radiation, W/m^2; ΔT is the temperature difference between greenhouse and outside air, ℃. Using Equation (1), it is easy to calculate the ventilation requirements for several values of $R_{s,o\text{-max}}$ and ΔT. The necessary ventilation rate can be obtained by natural ventilation or forced ventilation with ventilators located at the ridge, on the sidewalls and the gable, if possible. White and White et al.[21] recommended a total ventilator area equivalent to 15%-30% of the floor area. Over 30%, the effect of additional ventilation area on the temperature difference was very little.

The principle of forced ventilation is to create airflow through the greenhouse. Forced ventilation by fans is the most effective way to ventilate a greenhouse, but it consumes electricity. When not limited by too low external wind speed, natural ventilation could be more appropriate than forced ventilation. This results in reduced wind speed and higher temperature and humidity, as well as an increase in the thermal gradients within the greenhouse[22,23].

Natural or forced ventilation is generally not sufficient for extracting excess energy during sunny summer days[24]. The entry of direct solar radiation through the covers into the greenhouse enclosure is the primary source of heat gain. The entry of unwanted radiation (or light) can be controlled by shading or reflection. A method that is widely adopted by growers, because of its low cost, is white painting, or whitening of the cover material. Roof whitening with calcium carbonate on the external plastic cover for cooling purposes, given its low costs, is a common practice in the Mediterranean Basin. Whitening on glass material enhanced slightly the photosynthetically active radiation (PAR) proportion of the incoming solar irradiance[25]. This reduced the solar infrared fraction entering the greenhouse (a potential advantage) compared with other shading devices, especially in warm countries with high radiation load during summer.

Heating is a critical need in greenhouse industry especially during the winter seasons, since high humidity adversely affects plant development, possibly as a consequence of reduced transpiration rates and its impact on crop water requirement.

There are various ways to calculate greenhouse heating needs H_g (W). The simplest is given by ASAE[26] and the equation is as follows:

$$H_g=U\cdot A\cdot \Delta T \tag{2}$$

where, U is the heat loss coefficient, W/(m^2·K); A is the exposed greenhouse surface area, m^2. The estimation of greenhouse heating requirements using Equation (2) did not take into account heat loss due to leakage. It is a simple equation that can be used to estimate heating needs according to the greenhouse coverage area and the desired temperature difference between inside and outside air. The local climatic conditions necessary for siting a greenhouse are prerequisites for the generation of quality (accurate and representative) meteorological data. Accurate and representative weather data is paramount to the accurate estimation of ET_c in the greenhouse microclimate environment.

2.2 Integrity of greenhouse meteorological data for estimating ET_0

According to FAO-56, reference crop evapotranspiration (ET_0) which formed the basis of the adopted, utilized clipped, cool-season grass as a reference crop, is "the rate of evapotranspiration from a hypothetical crop, clipped, cool-season grass with assumed fixed height of 12 cm, the daily surface resistance of 70 s/m and the albedo of 0.23, approximately resembling the evapotranspiration from an extensive surface of a disease-free green grass cover of uniform height, actively growing, completely shading the ground, and with adequate water and nutrient supply". ET_0 is a critical factor for the accurate estimation of crop water requirements. Thus, accurate calculation methods for estimating daily ET_0 are important for proper irrigation scheduling in greenhouses[27-29].

In the greenhouse cultivation environment, meteorological data quality rather becomes more paramount for sustainable greenhouse production since the accurate estimation of ET_0 requires accurate and representative meteorological data[30]. According to Baudoin et al.[18], natural radiation conditions are the main limiting factor to quality meteorological data in the greenhouse which needs to be considered when establishing greenhouses, besides poor or malfunctioning weather station equipment. FAO proposed a methodology for achieving the required climate conditions that are the prelude to the acquisition of quality data in the greenhouses. These include characteristics of the cladding material; outside wind velocity; incident solar radiation; and transpiration of the crop grown inside the greenhouse[31]. During summer, solar radiation can dominate the ET_0 estimate, especially in humid and sub-humid climates. In winter, if solar radiation is low, wind speed and VPD can be strong drivers of the ET_0 calculation. Error in wind speed and VPD can dominate in greenhouses sited in arid and semiarid climates during summer[32-33]. The relative sensitivity of any one variable is impacted by the strength of the other weather variables.

In the greenhouse environment, crop transpiration is the main source of vapor besides evaporation from a wet surface. Vapor removal takes place through both condensation and ventilation so that the following balance equation holds:

$$E-C-V=0 \tag{3}$$

where, E is the crop transpiration; C is the vapor removed by condensation; V is the vapor removed by ventilation.

Relative humidity and VPD quantify the "drying power" of air that is the amount of vapor that air at a given temperature absorbs. Exchange of greenhouse air with the internal surfaces such as cover, crop, heating pipes, and soil surface is by convection, defined as the transport of energy flow from one place to the other in the direction of flow and the transport from a surface to a flowing medium or vice-versa. Convective heat transfers determine a large part of the microclimatic conditions inside a greenhouse[34]. Natural convection is expected inside the greenhouse due to low local air velocities generated by the existing temperature differences. However, forced convection is expected outside the greenhouse due to local air velocities generated by the wind field. The convective heat exchange is defined by the expression:

$$Q = \alpha_h\cdot A_s\ (T_a - T_s) \tag{4}$$

where, Q is the heat transfer per unit time, W; T_a is the ambient air temperature, K; T_s is cover surface temperature, K; A_s is the surface area, m^2; α_h is the heat transfer coefficient, W/(m^2·K). The integrity of the meteorological data is very much connected to the accurate estimation of ET_0 in the greenhouse.

3 Crop evapotranspiration prediction in greenhouse

Crop evapotranspiration (ET_c), under standard conditions, is the evapotranspiration from disease-free, well-fertilized crops, grown in large fields, under optimum soil conditions, achieving full production under the given climatic conditions. While crop water requirement accounts for the amount of water that needs to be supplied, ET_c refers to the amount of water that is lost through evapotranspiration. ET_c ranges between 1 to 9 mm/d from cool to warm average temperature[35].

Many empirical methods have been used for the determination of ET_c[36,37]. But of all these approaches, the most popular one is the standard FAO methodology[34,35]. FAO recommended a crop coefficient (K_c), which is the ratio of ET_c to ET_0, to estimate ET_c[38-41]. The FAO method estimates ET_c as the product of 1) reference evapotranspiration (ET_0), which quantifies the effect of climate on crop water demand; 2) the crop coefficient (K_c), which quantifies the effect of crop species and stage of development[35].

The current use of the Penman-Monteith equation is mainly to calculate ET_c for outdoor climates. Several methods have been developed for the estimation of ET_c based on 1) the aerodynamic principle; 2) the energy budget; 3) a combination of aerodynamic principle and the energy budget, and or 4) empirical principles. But the validity of most of the methods is often limited to specific geographic and climatic conditions[35]. In greenhouse analysis, estimation of ET_c has predominantly been conducted using the Penman-Monteith model[42]. A lot of mechanistic models using the Penman-Monteith method for ET_c estimation in greenhouses have been developed[7,9,11,43]. Boulard et al.[44], and Pollet and Bleyaert[45] used the Penman-Monteith formulation to validate a tomato crop transpiration model and also to calculate the ET_c of head lettuce in glasshouse conditions, respectively. However, their application of the Penman-Monteith method is still quite limited in scope since there is very little data on the aerodynamic and canopy resistances of cropped surfaces that are required by these models[46].

Inside plastic greenhouses in Mediterranean climate areas, the FAO-56 PM method accurately estimates ET_0 compared with a standard grass crop when using a fixed value of aerodynamic resistance of 295 s/m[46]. The FAO-24 pan evaporation method with a K_p (pan coefficient) constant of 0.79 provides good estimates of ET_0 in plastic greenhouses in Mediterranean environments. Hargreaves equation together with the Almería radiation model derived from the FAO-radiation equation developed, primarily for the Mediterranean conditions provide accurate estimations of ET_0. Given the limited climatic data requirements of the Hargreaves and the pan evaporation equations and their relative simplicity compared with the Penman-Monteith equation, these two methods are recommended for practical estimation of ET_0 in plastic greenhouses under Mediterranean climatic conditions[34,47].

The FAO K_c-ET_0 approach, besides its accuracy and reliability, is also inexpensive, requires limited meteorological data only to estimate ET_0 which is then multiplied by K_c value that represents the relative rate of ET_c and a specific condition[36,48]. There are mainly lysimeters used in conjunction with the soil-water balance approach to measuring ET_0 in plastic greenhouses and screenhouses, according to Fernández et al.[48] and Möller and Assouline[49]. The K_c-ET_0 has been a preferred approach for estimating the evapotranspiration flux in the greenhouse because of difficulties in applying inflow–outflow water balances. The K_c approach has the useful characteristics of being1) relatively consistent when transferred to new locations of use; 2) self-imposed empirical limits (0 to K_c max); 3) a relatively visual means of definition and construction of seasonal curves that ease the education of and adoption by new users; 4) relatively easy calibration and specification of parameters as compared to many mechanistic models.

Primarily, the K_c concept which has evolved into what is now known as "single" and "dual" crop coefficients gives rise to two methods used to estimate ET_c from ET_0: 1) single K_c method that integrates the combined effects of the two components of ET_0, i.e., crop transpiration (T_r) and soil evaporation (E)[35,50]; 2) dual K_c method which calculates T_r and E separately through a basal crop coefficient, K_{cb}, and a soil evaporation coefficient, K_e[36,51]. The single K_c is simple but the dual K_c method has the potential of improving the accuracy of ET_c estimation. Dual K_c takes into account soil wetting by irrigation and the effects of mulching, cropping, and agronomic management practices that may affect ET_c in the greenhouse[52,53].

4 Greenhouse technologies and ET_0 model or ET_c model

Greenhouse types depend much on the structure, construction method and material, facilities and equipment used for the greenhouse construction. Glass-covered greenhouses are mostly found in central and northern Europe. But in warmer climates, the majority of the greenhouses are covered with plastic films[54]. Globally, plastic film greenhouses are popular and have been readily adopted on all five continents, especially in the Mediterranean region, China and Japan compared with glass greenhouses[55]. Each type of greenhouse provides a different microclimate which affects the physical process of the ET_0 of a greenhouse canopy. Estimation of how much energy is to be absorbed by crop depends largely on the greenhouse characteristics (e.g., cladding materials, etc.) and the microclimate control mechanism (shading, screen, heating, and ventilation). Therefore, reliable estimations for plant water requirements must consider these factors before methods connecting ET_0 and the greenhouse microclimate can be formulated. Expansion of greenhouse production culture globally has led to the formulation of various models for ET_0 estimation which demands appropriate and reliable models for greenhouse microclimate conditions. Three categories of greenhouse types used globally based on the level of technology and their ET_0 models are considered, namely: low, medium and high technology.

4.1 Low technology greenhouse and ET_0 models used

Low technology greenhouses have low-cost structures covered with plastic film, without active climatic control systems and normally crops are grown on soil substrates. These greenhouses may be less than 3 m in total height especially for tunnel or igloos type of greenhouses[56]. Others are plastic greenhouse tunnels, screen-houses or insect netting structures having simple structures covered with nets. Natural ventilation is the common practice for this type of greenhouse[24,51].

Several ET_0 models including FAO Penman-Monteith, FAO Penman, FAO Radiation and Hargreaves-Samani in a low-cost plastic film low technology greenhouse structure were evaluated by Fernández et al.[48]. The study reported that calculated ET_c in the plastic greenhouse without whitening was best with FAO Penman and FAO Radiation models as most data were closely distributed around the 1:1 line of the measured ET_c. The FAO Penman and FAO Radiation had correlation coefficients (r^2) of 0.98 and 0.97 respectively. For Hargreaves-Samani model, the calculated ET_c was largely overestimated using the original equation[57]. By contrast, the FAO Penman-Monteith model underestimated the measured ET_c when the aerodynamic resistance (r_a) term in the calculations used was allotted higher values. For the greenhouse perennial crop, Fernández et al.[48] assumed a constant and lower value of r_a (150 s/m) which gave a better estimation of ET_c with the FAO Penman-Monteith model as compared to the measured ET_c with a relative error of 2.7 % and r^2=0.97.

4.2 Medium technology greenhouse and ET_0 models used

Medium technology greenhouses have better structures than low technology greenhouses and use facilities and equipment similar to that of high technology greenhouses for climate control. However, there is a limitation to the use of equipment compared to the high technology greenhouses. These types of greenhouses mostly use natural ventilation from the roof openings. Liu et al.[58] found that the ET_0 was best estimated using the FAO Penman model in a naturally ventilated greenhouse for banana crops. Comparison of five widely used ET_0 models of Priestly Taylor, FAO Radiation, Hargreaves-Samani, FAO Penman and FAO Penman-Monteith was evaluated. The study reported the correlation coefficient (r^2) as follows: FAO Penman (r^2=0.67), followed by FAO Penman-Monteith (r^2=0.67), FAO Radiation (r^2=0.63), Hargreaves-Samani (r^2 = 0.52) and Priestley Taylor (r^2 = 0.47). The FAO Penman model and FAO Penman-Monteith gave higher correlation coefficients than the others and in both models, wind speed was considered in the ET_0 calculation modules while in FAO Radiation, Hargreaves-Samani and Priestley Taylor models, calculations were based on radiation only. These radiation-based models are suitable for no or low advective conditions under no or low wind speed. Moreover, the study found that the ET_0 was largely dependent on the VPD and air temperature in the greenhouse. López-Cruz et al.[59] compared two theoretical models of FAO Penman-Monteith and Stanghellini model for a tomato crop. Results showed that due to a more detailed estimation of net radiation, LAI and a better estimation of the stomatal resistance of the tomato crop, the Stanghellini model (r^2=0.72) performed better than FAO Penman-Monteith (r^2=0.62). Stanghellini model which included the input parameter LAI was the reason for better ET_c estimation, especially for the greenhouse crop. Takakura et al.[42] measured the ET_0 with a simple energy balance equation for a fully grown tomato crop in a single-span greenhouse with natural ventilation. The values estimated by this method were in good agreement with the measured data using sap flow meters and water consumed by fog cooling which gave a correlation coefficient, r^2=0.677, and 0.725 when soil heat flux was neglected.

4.3 High technology greenhouse and evapotranspiration models used

High-technology greenhouses commonly are closed-type greenhouses where the environment is controlled. This type of greenhouse is well equipped with various automation integrated with controlled systems management. Stanghellini[60] and Fynn et al.[61] models represent evapotranspiration models for the high technology greenhouse. Stanghellini developed a model which accounts for the relationship between the microclimate and the transpiration of a greenhouse canopy in a single glass, Venlo-type greenhouse with water pipe heating. Energy balance method was employed to appraise the relationship between the transpiration rate of a greenhouse tomato crop and the microclimate. Stanghellini model proved to be practically useful for evapotranspiration estimation in a high technology greenhouse.

Fynn et al.[61] estimated ET_c of potted chrysanthemum crop in a controlled shading and energy conservation greenhouse. Fynn's model considered the ET_c estimation for only the area of a greenhouse floor covered by the canopy. Assumptions made in the equation were: 1) energy exchange is adiabatic in the form of water vapor between the canopy and the surrounding environment as a result of vapor pressure and temperature differences; 2) solar and long-wave radiation exchanged from the canopy. Fynn et al.[61] reported that the model can accurately predict the water requirements and environmental responses of a potted chrysanthemum. Prenger et al.[62] evaluated four ET_c models: FAO Penman, FAO Penman-Monteith, Stanghellini and Fynn for the ET_c of Red Sunset red maple trees in a climate-controlled greenhouse. Stanghellini model calculated the best ET_c as compared to the ET_c measured by a lysimeter with the highest correlation coefficient, r^2=0.958. This was closely followed by Fynn (r^2=0.940), FAO Penman-Monteith (r^2=0.886) and FAO Penman (r^2=0.872). The calculations with FAO Penman-Monteith and Penman models overestimated the ET_c.Stanghellini model provided a more accurate prediction with a close correlation as the model was adapted for the actual leaf surface area, whereas, in Fynn's model, the canopy surface area proportional to the floor area was taken as an assumption for the energy exchange. ET_c calculation with FAO Penman-Monteith has the advantage of simplicity and reliability if r_c is correctly estimated and if measurement or calculation of canopy net radiation is available.

Baille et al.[13] used a simplified model in yet another study for predicting $ET_c$of nine greenhouse ornamental species. The species were *Begonia, Cyclamen, Gardenia, Gloxinia, Hibiscus, Impatiens, Pelargonium, Poinsettia* and *Schefflera*. The indoor greenhouse climate of solar radiation, VPD and LAI were surveyed and correlations were made based on the Penman-Monteith equation. Results indicated that the ET_c for the nine ornamental species under the greenhouse conditions gave satisfactory results. ET_c calculated at day time with the measured ET_c have correlation coefficient (r^2) between 0.87 and 0.97. Greenhouse climatic conditions which are a product of the level of technological investment also primarily determine the type of weather data to be collected from the greenhouse. Table 1 summarises the categories of greenhouses, equipment used and the data collected for ET_0 measurements.

Table 1 Greenhouse categories, equipment used, input data measured and references

Greenhouse category	Greenhouse description	Equipment	Input data measured	Reference
Low technology	Plastic greenhouse	Lysimeter	R_n, u, T_a	Fernández et al[48]
	Screen-house	Lysimeter	R_n, u, T_a	Möller et al[63]
	Screen-house	Lysimeter	R_n, u, T_a	Möller and Assouline[49]
	Screen-house	Eddy covariance (EC)	R_n, u, T_a,VPD	Pirkner et al[57]
Medium technology	Natural ventilation	Lysimeter	R_n, u, T_a, PAR	López-Cruz et al[59]
		Sap flow meter	R_n, u, T_a, PAR	Takakura et al[42]
		Load cells	R_n, u, T_a, PAR	Liu et al[58]
		Water balance method	R_n, u, T_a, PAR	Valdés-Gómez et al[64]
High technology	Controlled environment	Electronic weighing balance	R_n, VPD, LAI, T_a, T_l	Prenger et al[62]
		Lysimeter	R_n, VPD, LAI, T_a, T_l	Fynn et al[61]
		Electronic weighing balance	R_n, VPD, LAI, T_a, T_l	Baille et al[13]

In order to select an appropriate model for a specific greenhouse microclimate, an accuracy level assessment of ten models widely used was made. Comparisons between calculated and measured ET_0 and ET_c in the various greenhouse categories in each study based on available literature data were done. The models were compared and arranged according to their accuracy levels. Three kinds of greenhouses were distinguished for the low technology greenhouse alone, including low structure plastic greenhouse, with and without whitening and screenhouses as summarized and presented in Table 2. The FAO Penman and Penman-Monteith were obviously the most widely used models in this type of greenhouse. Temperature and radiation-based Hargreaves-Samani model was also used quite often according to literature from the various studies cited. Complex models such as Stanghellini and Fynn were not found as ET_0 and ET_c models in low technology greenhouse according to literature precisely because these models were developed mainly for the controlled environment greenhouse conditions.

Unlike the low technology greenhouses, both simple and complex models have been used in the medium technology greenhouse. The best option for the ET_c estimation in a naturally ventilated, medium technology greenhouse is the Stanghellini model. Stanghellini model was developed for the conditions of a greenhouse which incorporates LAI as an input parameter. LAI is an important parameter that influences the calculation of transpiration from a leaf surface area. In high technology greenhouses, studies have confirmed that Stanghellini, Fynn, FAO Penman-Monteith, FAO Penman and Simplified Penman-Monteith models are arguable, complex models with high accuracies can be applied in this type of greenhouse (Table 2). These models take into account the input parameter for the greenhouse microclimate especially LAI, *VPD*, leaf or canopy (stomatal) resistance and the exact amount of radiation received by the greenhouse canopy.

Table 2 Accuracy levels assessment of ET_0 and ET_c models in Greenhouse categories

Greenhouse category	Greenhouse description	Greenhouse crop	ET_0 or ET_c model	Accuracy level	R^2/ RE/ $RMSE$	Reference
Low technology	Plastic (without whitening)	Perennial grass	FAO Penman	1	$R^2=0.98$, $RE=1.7\%$	Fernández et al[48]
		Perennial grass	FAO (PM) ($r_a=150$ s m^{-1})	2	$R^2=0.97$, $RE=2.7\%$	Fernández et al[48]
		Perennial grass	FAO Radiation	3	$R^2=0.97$, $RE=-3.7\%$	Fernández et al[48]
		Perennial grass	Hargreaves (with greenhouse transmissivity)	4	$R^2=0.97$, $RE=3.7\%$	Fernández et al[48]
	Plastic (with whitening)	Perennial grass	Hargreaves (with greenhouse transmissivity)	1	$R^2=0.97$, $RE=-2.6\%$	Fernández et al[48]
		Perennial grass	FAO PM ($r_a=150$ s m^{-1})	2	$R^2=0.98$, $RE=8.5\%$	Fernández et al[48]
		Perennial grass	FAO Radiation	3	$R^2=0.98$, $RE=-0.7\%$	Fernández et al[48]
		Perennial grass	FAO Penman	4	$R^2=0.98$, $RE=-1.6\%$	Fernández et al[48]
	Screenhouse	Sweet pepper	Penman-Monteith	1	$R^2=0.94$, $RE=3.8\%$	Möller et al[63]
		Sweet pepper, banana	FAO Penman-Monteith	2	$R^2=0.93$	Pirkner et.al[57]
Medium technology	Natural ventilation	Tomato	Stanghellini	1	$R^2=0.72$, $RMSE=2.4$	López-Cruz et al[59]
		Tomato	Energy balance equation	2	$R^2=0.68$	Takakura et al[42]
		Banana, tomato	FAO Penman	3	$R^2=0.63$, $RE=-3.7\%$	Liu et al[58]
		Banana, tomato	Priestley-Taylor	4	$R^2=0.63$, $RE=6.1\%$	Valdés-Gómez et al[64]
		Banana	FAO Penman-Monteith	5	$R^2=0.63$, $RMSE=17.1$	Liu et al[58], López-Cruz et al[59]
		Banana	FAO Radiation	6	$R^2=0.52$	Liu et al[58]
		Banana	Hargreaves	7	$R^2=0.49$	Liu et al[58]
			Priestly-Taylor	8	$R^2=0.47$	Liu et al[58]
High technology	Controlled environment	Tomato, red sunset	Stanghellini	1	$R^2=0.96$, $RMSE=0.006$	Stanghellini60], Prenger et al[62]
		Chrysanthemum, red sunset	Fynn	2	$R^2=0.94$, $RMSE=0.021$	Fynn[61], Prenger et al[62]
		Red sunset	FAO Penman-Monteith	3	$R^2=0.89$, $RMSE=0.016$	Prenger et al[62]
		Red sunset	FAO Penman	4	$R^2=0.87$, $RMSE=0.179$	Prenger et al[62]
		Ornamental species	Simplified model	5	R^2=0.87-0.97	Baille et al[13]

Note: R^2: Coefficient of correlation; RE: Relative error; $RMSE$: Root mean square error; accuracy level defined as “1” represents the most accurate; “2” represents the more accurate; “3” represents the accuracy; “4,5,6,7,8” represent the gradual decline of the accuracy level.

5 Recommendation

The fast development of the greenhouse farming system globally has occasioned the necessity to provide vegetable crops with their exact water requirements to improve and enhance the efficiency of irrigation water management within the greenhouse microclimate. The current application of the FAO recommended Penman-Monteith formula for ET_c estimation in a greenhouse microclimate is still quite limited in scope due to 1) inadequate information on the aerodynamic and canopy resistances (generally fixed estimated values are used) of cropped surfaces that are required by the greenhouse models[11]; 2) unavailability of climatic variables (especially R_s, T_a, RH and wind speed); 3) climatic data in many developing regions cannot always meet the strict requirements of the FAO-56 PM method for calculating ET_c, and consequently, the results are uncertain for greenhouse crops under different convection regimes[1,36]. For a more innovative approach to calculating ET_c in a greenhouse by the Penman-Monteith modified formula, it is suggested that, an innovatively simplified model for the calculation of ET_c in the greenhouse based on the energy balance equation, which can correlate the ET_c, radiation and temperature be pursued. This method will require less meteorological data and thus appears to be simple and more desirable for wider application compared with the current model.

The FAO Penman-Monteith overestimates the ET_c in the greenhouse, even though it is the globally accepted standard and optimal model developed solely for outdoor open field conditions[62]. The ET_c equations based on temperature and humidity report better results than equations based on solar radiation only, as evidenced by the Priestley-Taylor model which incorporates the use of the microclimatic data of the greenhouse[65]. Complex models by Stanghellini and Fynn that predicted more accurate ET_c can be made simpler to be used in low technology greenhouses by the incorporation of more climatic parameter measurements. The inconsistency in the ET_c models accuracies estimated in the medium technology greenhouse calls for further research, re-packaging and re-evaluation. The development of new models or having a known adjustment factor for the medium technology greenhouse conditions calls for further research in this area. Further evaluation and analysis are required to re-calibrate and re-validate these models with actual greenhouse microclimatic data especially for conditions in different types of greenhouses[66-68].

Research on ET_c models for greenhouse crops is insufficient and the parameters are difficult to obtain, but also, mostly focused on the soilless culture (hydroponics) and the Mediterranean climatic condition. Recent new advances in research, data availability, modelling capabilities and how the methodology responds to new challenges and demands in the field of crop water relationships call for re-evaluations of past and current empirical models for ET_c estimation to make it more globally user-friendly. Re-calibration innovation and modification of ET_c to cater for local and regional differences in climatic conditions in order to obtain reasonable ET_c measurements or estimates has been emphasized time and again[69-71].

In certain environmental jurisdictions, it is not always possible to measure climatic data inside of the greenhouse due mainly to lack of facilities and equipment, expertise and economic reasons. Therefore, using available climatic data especially from nearby weather stations which give outside greenhouse climatic data might be useful. In order to fully utilize outside data, an appropriate well-documented method through a correlation that could lead to inside condition might be a solution. It can be said that the adoption of common and simple ET_c models capable of measuring quite accurately can reduce the cost of irrigation management.

6 Conclusions

A wide spectrum of greenhouse ET_c models is now available and efforts should focus on making these models trustworthy and easy to use by researchers, authors, students as well as greenhouse farmers. In pursuit of this, it is important to match specific greenhouse microclimatic environment and technological investments with the ET_c models. In the brief overview presented in this paper, we have highlighted a link between greenhouse technology and ET_0 and ET_c models, and how existing knowledge and methodologies in ET_c measurements can favorably enhance the sustainability of greenhouse farming.

Greenhouse climatic conditions, a product of the level of technological investment primarily determine the type of meteorological data to be collected from the greenhouses. However, each type of greenhouse provides different microclimates which affect the physical process of the ET_c. Thus, reliable estimations for plant water requirements must consider greenhouse characteristics and microclimate control mechanisms before methods connecting ET_c and the greenhouse microclimate can be formulated.

The categories of greenhouses, equipment commonly used and the data collected for ET_c measurements have been established in the text. Accuracy level assessment of ten widely used ET_0 and ET_c models was made.

The estimation of ET_0 by measuring the greenhouse microclimatic data revealed that the FAO Penman and FAO Penman-Monteith are best suited to conditions in low technology plastic greenhouses. Stanghellini model estimate ET_c best in the medium technology greenhouse. Stanghellini, Fynn, FAO PM, FAO Penman and Simplified PM models had proved to be practically useful for ET_c estimation in a high technology greenhouse. This also indicates that these models can best be used in greenhouses only when parameterization of the aerodynamic and canopy resistances based on actual meteorological and crop data measurements within the greenhouse is conducted.

In conclusion, it is anticipated that this overview of modelling techniques for greenhouse microclimate control and ET_c will serve as a useful didactic tool to teach about the link between greenhouse technology and ET_c models. This, it is believed will have far-reaching impacts on researchers and greenhouse farmers in our bid to provide vegetable crops with their exact water requirements to improve and enhance the efficiency of irrigation water management in greenhouses.

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