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State of the art of evapotranspiration models for plant cultivation in open fields, greenhouse systems and plant factories

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Abstract. The scarcity of water, the need to reduce of pesticides, the demand for on-site production of vegetables are moving the interest from greenhouse cultivation to indoor farming. Compared to greenhouses, indoor farms allow to reduce considerably the water consumption, requiring more energy, which could be provided by renewable sources. In order to assess the convenience of such a system, accurate preliminary calculations are needed for productivity, energy requirements and costs as a function of the type of cultivation and the operating conditions. While some knowledge (e.g. production rate or cooling system performance) are available from open literature, some specific predictive methods are required. Based on the few works available in literature about indoor farming, evapotranspiration rate resulted as a critical term. An assessment of different methods based on literature data with a critical analysis of their effectiveness based on several aspects (level of fidelity of the model, complexity in the calibration and use, potential strengths and weaknesses) is proposed in this work.

1. Introduction

1.1. Context

Nowadays, due to the constant global population growth, urbanization, pests use, climate change, resource degradation and scarcity, the water-energy-food nexus is constantly stretched and strongly tested. First of all, agricultural sector is the bigger user of water resource: it accounts for 70% of the total global freshwater withdrawals [1]. In addition, energy consumption in the agricultural sector accounts for 3% in the European scenario [2] and energy demand will increase about 3 times by 2050 worldwide [3]. On the other hand, it is expected that the global population will reach 9.8 billion by 2050 and 11.2 billion by 2100 [4]: moreover, the intense urbanization will affect more than 70% of world population. Furthermore, about 1.9 Mtons of pesticides and chemical substances have been employed in agricultural sector during 2019 in the European scenario [5, 6]. Due to the above-mentioned reasons along with the increasingly intense land scarcity, alternative and sustainable technologies for the agricultural sector are necessary.

1.2. Main advantages and disadvantages of indoor farming systems
One of the most promising and potentially sustainable system in the agricultural context is represented by the indoor farming method in a completely closed and controlled environment, the so-called plant factories (PFs) or vertical farms (VFs). Vertical farm consists of a well-insulated structure within which the optimal conditions for plant growth in terms of temperature and relative humidity are achieved. Crops are placed on several layers in a vertical direction and the whole system is equipped with lighting devices able to replace solar incoming radiation such as LED systems or fluorescent lamps. Air conditioning systems are used for cooling and dehumidification purposes; CO_2 units are placed in order to control CO_2 level inside the system. Finally, PFs are equipped with supply nutrient-solution and water source systems [7, 8].

Is it worth noting that PF systems involve several advantages compared to standard cultivation methods such as open field and traditional greenhouse systems. In fact, PFs productivity is higher and more stable compared to other plant production systems as it is independent of external climatic conditions. Thanks to CO_2 and water savings, crop safety and healthiness PFs are becoming widespread both in very cold climate regions in which solar radiation is very low and in arid ones where water consumption in greenhouse systems can be related also to temperature control strategies such as evaporative cooling [9]. On the other hand, drawbacks in the PF systems regard the investment costs and the energy consumption, which are significantly higher compared to the ones of traditional greenhouse systems [10 – 12]. Efforts and challenges of indoor cultivation methods can be carried out in terms of improvement of LED efficiency or their integration with renewables [13].

1.3. Motivation and objectives of the work
Due to their complexity, the design of the aforementioned systems requires the correct evaluation of all the system characterizing loads. Among them, a fundamental role is associated to the evapotranspiration (ET) rate of the plants, which represents the amount of the vapour water lost from the leaf surface to the surrounding atmosphere. The correct evaluation of the ET rate of the plants in completely-closed and controlled systems is of primary importance for their energy characterization.

ET can be considered as the combination of the water evaporation from the soil to the environment and water transpiration from the leaf stomata to the environment. It depends on several factors, such as the vapour difference between water vapour in the leaf surface and the one in the ambient air, the solar radiation and the meteorological conditions, air temperature and humidity, wind speed and crop characteristics. In order to evaluate ET rate of the plants, models that accurately estimate the load are necessary. For the above-mentioned reasons, the primary goal of the present work is to deepen and investigate existing methods in literature for ET rate evaluation in open field and traditional greenhouse systems in order to understand their potentialities and highlight their limitations to determine their applicability to PF systems. For this purpose, a detailed analysis of the well-known existing methods is proposed by considering all the influencing factors on the ET rate phenomenon.

2. State of the art of evapotranspiration models
Several evapotranspiration models have been developed in literature in order to estimate the quantity of vapour leaving the leaf surface. This section provides a general overview of the most used and well-known predictive methods of evapotranspiration rate, describing their potentialities and underlying their drawbacks and limits.

2.1. Penman-Monteith
In the Penman-Monteith [14] model the three-dimensional canopy is assumed as a one-dimensional big leaf. The equation of [14] is based on the combination of the heat and mass transfer and it takes into account both meteorological data and plant characteristics. The original equation is:

$$ET = \frac{1}{\lambda} \cdot \frac{\Delta(R_n - G) + \rho_a c_p \left(\frac{VPD}{r_a}\right)}{\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)} \quad (1)$$

In Eq. (1) λ is the latent heat of vaporization, Δ is the slope of the saturation vapour pressure curve, R_n is the net solar radiation, G is the soil heat flux, ρ_a is the mean air density, c_p is the specific heat of air, VPD is the vapour pressure deficit, γ is the psychometric constant, r_s is the stomatal resistance and r_a is the aerodynamic resistance. In the model, both surface and aerodynamic resistances are taken into account. As regards the surface term, it represents the leaf resistance to the vapour transport through stomata into the surrounding air and it can be expressed as a function of the leaf area index (LAI) and the bulk stomatal resistance of a well-illuminated leaf (r_i):

$$r_s = \frac{r_i}{LAI} \quad (2)$$

The aerodynamic resistance is instead the resistance to the vertical water vapour diffusion from the leaf to the surrounding air and it is expressed by considering the logarithmic wind profile as reported in Eq. (3):

$$r_a = \frac{\ln\left(\frac{z_m - d}{z_{om}}\right)\ln\left(\frac{z_h - d}{z_{oh}}\right)}{k^2 u_z} \quad (3)$$

In the previous equation, z_m is the height of the wind measurement, z_h is the height of humidity measurement, z_{om} is roughness length of momentum transfer, z_{oh} is the roughness length of heat and vapour transfer, d is the height at which the wind speed is zero, k is the Von Karman constant (0.41) and u_z is the wind speed measured at height z.

Several studies have implemented the Penman-Monteith equation [14] in order to evaluate the evapotranspiration rate of different crops. Villareal-Guerrero et al [15] found that the model overestimates the evapotranspiration rate of bell pepper and tomato in greenhouse system located in Arizona (R-square between 0.51 and 0.95). The same conclusion is reported in Zhang and Lemeur [16], in which the evapotranspiration rate of Ficus Benjamin is evaluated. Zolnier et al [17] stated that Penman-Monteith equation [14] provides a good agreement in the evapotranspiration rate estimation for three lettuce cultivars in a greenhouse system located in Brazil (R-square between 0.82 and 0.93).

2.2. Priestley-Taylor

Priestley – Taylor [18] method replace the aerodynamic resistance to the vapour transfer with a dimensionless coefficient α in the Penman-Monteith equation [14]. The authors suggested a value of 1.26. The evapotranspiration rate equation becomes:

$$ET = \frac{\alpha}{\lambda} \cdot \left(\frac{\Delta}{\Delta + \gamma}\right)(R_n - G) \quad (4)$$

In Eq. (4) α is the Priestley-Taylor coefficient. Tabari et al [19] provided a calibration of the Priestley-Taylor coefficient and they found a value of 1.82 for cold Iranian region climate and 2.14 for arid Iranian region climate. In the study of Sharma et al [20] the model showed an underestimation of the evapotranspiration rate of chile peppers by 17.5-37% in a greenhouse located in Mexico.

2.3. Hargreaves-Samani

In this model the evapotranspiration rate is evaluated only through the daily temperature values and solar radiation, as shown in Eq. (5):

$$ET = \frac{1}{\lambda} \cdot 0.0023(T_{max} - T_{min})^{0.5}\frac{(T_{max} + T_{min})}{2} R_a \quad (5)$$

In the previous equation T_{max} is the maximum daily temperature, T_{min} is the minimum daily temperature and R_a is the extra-terrestrial solar radiation. Solar radiation instead is evaluated as:

$$R_s = k_{RS}(T_{max} - T_{min})^{0.5} R_a \tag{6}$$

In Eq. (6) k_{RS} is an empirical coefficient set at 0.16 °C$^{-0.5}$ for interior regions and 0.19 °C$^{-0.5}$ for coastal regions. Due to the adjustment factors, the model provides a high overestimation of evapotranspiration rates. Several studies have calibrated Hargreaves-Samani [21] model: Fernandez et al [22] found an overestimation of ET rate of 66% in a Mediterranean greenhouse and modified the solar radiation term. The same conclusion was achieved by Jaafar and Ahmad [23]. Berti et al [24] calibrated the empirical adjustment coefficient for north-eastern region of Italy and determined a common value of 0.002 with a significant reduction of the model overestimation.

2.4. Stanghellini

Stanghellini model [25] is based on the Penman-Monteith [14] equation by including the multilayers effect of the crop:

$$ET = \frac{1}{\lambda} \cdot \frac{\Delta(R_n - G) + \left(\frac{2LAI\rho_a c_p}{r_a} VPD\right)}{\gamma \cdot \left(1 + \frac{\Delta}{\gamma} + \frac{r_s}{r_a}\right)} \tag{7}$$

In Eq. (7) LAI is the leaf area index, the ratio between the total area of the leaf and the cultivation surface area. In the model the net solar radiation is evaluated by combining shortwave and longwave radiation:

$$R_n = 0.07 \cdot I_s - \frac{0.16\rho_a c_p (T_a - T_s)}{r_R} \tag{8}$$

In Eq. (8) I_s is the incoming solar radiation and r_R is the radiative resistance, which is expressed as follows, with σ the Stefan-Boltzmann constant:

$$r_R = \frac{\rho_a c_p}{4\sigma T_a^3} \tag{9}$$

The aerodynamic resistance r_a is evaluated through the Nusselt number:

$$r_a = \frac{\rho_a c_p l}{\lambda_a Nu} \tag{10}$$

In Eq. (10) λ_a is the thermal conductivity. Nusselt number is instead expressed as follows:

$$Nu = 0.37 \cdot \left[Gr + 6.92 Re^2\right]^{0.25} \tag{11}$$

In Eq. (11) Gr and Re are respectively Grashof and Reynolds number. Villareal-Guerrero et al [15] found that the Stanghellini model [25] better estimates the ET rate compared to Penman-Monteith [14] and Takakura [26] ones, with a percentage error between -5.5% and 7%. Pamungkas et al [27] instead found that the model overestimates the ET rate.

2.5. Fynn

The Fynn [28] method was derived from Stanghellini [25] one. This model is based on the assumption that the saturated vapor pressure at leaf temperature is approximated to the saturated vapor pressure at air temperature if the difference between leaf and air temperature is quite low, around 4-5°C. Moreover, evaluation of the radiation flux provided by Stanghellini [25] is not included in this model; consequently, the evapotranspiration rate equation is expressed as follows:

$$ET = \frac{1}{\lambda} \cdot \frac{[2LAI\rho_a c_p (VPD/r_a)] + \Delta(R_n - G)}{\gamma\left[1 + \frac{r_s}{r_a} + \frac{\Delta}{\gamma}\right]} \tag{12}$$

Prenger et al [29] compared the model with Penman-Monteith [14] and Stanghellini [25] ones and the authors found that the model provided the higher underestimation of evapotranspiration rates (about 45%). Therefore, a modification of it is proposed by Prenger et al [29]: in order to better evaluate the radiation flux the canopy area index (the ratio between the canopy area and the controlled environment systems floor area) was included.

2.6. *Baille*

Baille [30] proposed a modification of the Penman-Monteith [14] method for evapotranspiration rate estimation in which K_1 and K_2 coefficient replace crop parameters of [14]. The evapotranspiration rate is evaluated as follows:

$$ET = \frac{1}{\lambda}[K_1 \cdot R_n(1 - \exp(-e_k LAI)) + K_2 \cdot LAI \cdot VPD] \tag{13}$$

In the previous equation K_1 and K_2 represent regression coefficient depending on the crop type and climate variables, R_n is the net solar radiation and e_k is the extinction coefficient set equal to 0.64. In Medrano et al [31] coefficient K_2 is calibrated for cucumber cultivation in a greenhouse system located in Almeria. Authors found an overestimation of evapotranspiration rate up to 9%. Battista et al [32] calibrated the abovementioned coefficients for different crop type and climate conditions in an Italian greenhouse. The estimation error was found to be less than 5%.

2.7. *Takakura*

Takakura et al [26] method is based on the energy balance on the leaf surface and the equation for the evapotranspiration rate estimation is the follow:

$$ET = \frac{1}{\lambda}\left[(R_n - G) - h\left[\frac{T_{max} + T_{min}}{2} - T_w\right]\right] \tag{14}$$

In Eq. (14) h is the heat transfer coefficient, T_{max} and T_{min} are the maximum and minimum daily temperature, respectively and T_w is the wet surface temperature. In order to evaluate the solar radiation, different sensors for short wave and long wave radiation are necessary and a calibration by using both a solarimeter (for short wave radiation sensor) and an infrared thermometer (for long wave radiation sensor) is required. Heat transfer coefficient h is a function of the wind speed and the authors found a relationship with a R^2 equal to 0.52. Takakura et al [26] method was compared with Stanghellini [25] and Penman-Monteith [14] by Villareal-Guerrero et al [15] and authors found that Takakura et al [26] model overestimates the evapotranspiration rate of bell pepper and tomato in greenhouse system located in Arizona (R^2 from 0.86 to 0.93) in the early morning hours whereas it underestimates evapotranspiration rate in the remaining hours.

2.8. *Graamans*

Graamans et al [33] model is a modification of the Penman-Monteith [14] equation by considering a lettuce canopy in a plant factory system. In the method of Graamans et al [33] an iterative process is implemented in order to evaluate the leaf temperature by respecting the energy balance on the leaf. The evapotranspiration rate equation is:

$$ET = LAI \cdot \frac{VCD}{r_s + r_a} \tag{15}$$

In Eq. (15) VCD is the vapour concentration deficit. The surface resistance to the vapour transfer is estimated to be a function of the photosynthetic photon flux density (PPFD) as shown in Eq. (16):

$$r_s = 60 \cdot \frac{1500 + PPFD}{200 + PPFD} \tag{16}$$

The [14] method also includes a submodel for the aerodynamic resistance even though authors used a constant value of r_a equal to 100 s/m in case of forced air circulation and 200 s/m in case of natural air circulation. The submodel for aerodynamic resistance is:

$$r_a = 350 \cdot \left(\frac{l}{u}\right)^{0.5} \cdot LAI^{-1} \tag{17}$$

In the previous equation l is the mean leaf diameter and u is the uninhibited air velocity.

3. Assessment of the evapotranspiration rate predictive methods

In this section a comparison between the ET rate predictive methods is carried out, in order assess their applicability to a completely-closed and controlled environment depending on their strengths/weaknesses.

Figure 1 provides a comparison between the measured evapotranspiration rate values and the predicted ones by Penman-Monteith [14], Stanghellini [25] and Graamans [33] models. Operating parameters are reported in Villareal-Guerrero [15] from Figure 2.

All the employed models have been previously calibrated and a statistical analysis has been carried out. It was found that for the actual conditions, Penman-Monteith [14] largely overestimates ET rate, with a percentage error of 46% during the lighting hours. Stanghellini [25] ET rate predictive method provides a very good agreement with the experimental data and a percentage error of 3% was found during the lighting period. Finally, Graamans et al [33] ET rate model generally overestimates evapotranspiration rate and a percentage error of 36% between experimental and predicted values during the lighting hours is achieved.

It is worth noticing that the trend of the predictive methods experienced for the simulation reported in Figure 1 is not general. The authors have run also other simulations and the agreement between the experimental data and the predictions is sometime favourable also to the Penman-Monteith method. In facts, the methods by Penman-Monteith and Stanghellini require the calibration of the surface and aerodynamic resistances. This calibration has been done by Villareal-Guerrero with an optimization procedure on the whole set of data for the aerodynamic resistance, while on a single day data for the surface resistance. Consistently, sometimes the predictions of some method could fit particularly well the experimental data.

In addition to the previous comment related to the effect of the calibration (which is always dependent on the specific set of data considered), as a more general consideration it is important to underline that the model by Stanghellini is physically more sound than the one by Penman-Monteith, since it includes the actual contact surface between the crops and the moist air via the LAI.

4. Conclusions

A state of the art of the existing well-known predictive methods of evapotranspiration rate of crop cultivations have been carried out in this study. Both open field and indoor farming methods have been considered, underlying their potentialities and limits.

By considering the operating parameters reported in Villareal-Guerrero [15], the assessment of the existing predictive methods has shown that the Penman-Monteith [14] and Graamans et al [33] ones generally overestimate evapotranspiration rate; on the other hand, Stanghellini [25] method provides a very good agreement with the experimental data. Statistical analysis provided a percentage error of 46%, 36% and 3%, respectively.

Regarding the complexity of the implementation of each model, they generally require a calibration of some coefficients related to the boundary conditions (like the net solar radiation, the type of cultivation, the LAI, the surface and the aerodynamic resistances). Also, it was found that independent parameters affecting ET rate could in some experimental conditions be inter-related, due to the specific operating conditions: this causes a bad fitting of the experimental data with potentially wrong predictions when the operating conditions are outside the range of calibration and/or difficulties in the calibration process. In terms of trends, the method, which capture it better, is the one by Stanghellini.

Regarding the accuracy of the predictions, the results of the assessments in literature return sometime contradictory results, depending on the quality of the calibration process and/or on the data available.

For all the aforementioned reasons some aspects related to the ET predictions should be deepen, especially for systems which have been poorly studied, such as indoor farms.

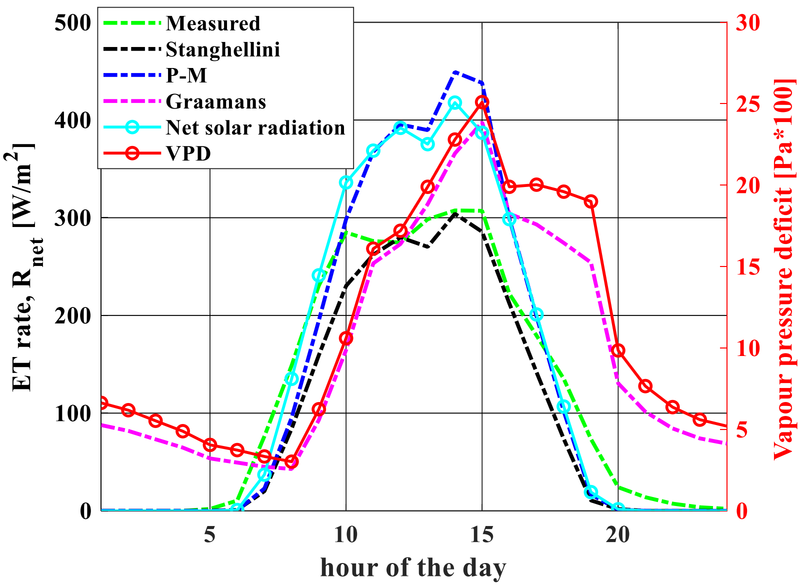

Figure 1. Measured evapotranspiration rate and predicted one by Stanghellini [25], Penman-Monteith [14] and Graamans [33] models, net solar radiation and vapour pressure deficit.

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