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Derleme/Review

Equations Developed to Estimate Evapotranspiration in Greenhouses

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Abstract: It is estimated that the world population will be 9.6 billion by 2050. In order to meet the food needs of the growing population, it is necessary to increase the yield obtained from existing agricultural land. As the greenhouse provides a more controlled environment, the yield taken from the unit area is higher than the field conditions. For this reason, the greenhouse cultivation has been increased in year by year. Irrigation is one of the major cultural applications for increasing yield from the unit area. It is important that crop water requirement should be determined correctly for proper irrigation scheduling in greenhouse. The use of equations based on climate to determine evapotranspiration has been increased in recent years. In this study, estimation performances of evapotranspiration equations based on the reference crop (Penman, Hargreaves, FAO-24-Radiation, Priestley-Taylor, FAO-Penman Monteith, FAO24-Pan Evaporation) and main crop (Stanghellini, Fynn, Takakura, Simplified Model) developed from the past to the present day were reviewed. It is concluded that there is no standard equation under greenhouse conditions to determine evapotranspiration of a specific crop. The reason for this is that greenhouse climate changes depending on greenhouse type, location, direction, cover material, greenhouse volume, ventilation mechanism, usage of thermal curtain and shadow powder and even cultural applications such as hanging. However, it is possible to develop new equation or calibrate existing equations for each different greenhouse in the same region. Therefore, it is suggested that evapotranspiration equations to be used should be selected depending on the type of greenhouses commonly used in the region and, if necessary, modified according to these conditions.

Keywords: Aerodynamic resistance, Climate data, Crop evapotranspiration, Reference evapotranspiration, Vapor pressure deficit

Seralarda Evapotranspirasyon Tahmini için Geliştirilen Denklemler

Öz: Dünya nüfusunun 2050 yılında 9.6 milyar olacağı tahmin edilmektedir. Artan nüfusun gıda ihtiyacının karşılanabilmesi için mevcut tarım arazilerinden alınan verimin arttırılması gerekmektedir. Seralar daha kontrolü bir ortam sağladığı için birim alandan alınan verim tarla koşullarına kıyasla daha fazladır. Bu nedenle seraların kullanımı son yıllarda giderek artmaktadır. Birim alandan alınan verimin artırılması için en önemli kültürel uygulamaların başında sulama gelmektedir. Sera koşullarında uygun bir sulama programlaması için bitki su tüketiminin doğru belirlenmesi önemlidir. ET'nin belirlenmesi için iklime dayalı eşitliklerin kullanımı son yıllarda artmaktadır. Bu çalışmada geçmişten günümüze kadar kıyas bitkiye (Penman, Hargreaves, FAO-24-Radiation, Priestley-Taylor, FAO-Penman Monteith, FAO24-Pan Evaporation), ve esas bitkiye dayalı (Stanghellini, Fynn, Takakura, Simplified Model) geliştirilmiş olan ET eşitliklerinin tahmin performansları incelenmiştir. Çalışma sonucunda sera koşullarında standart bir yöntemin bulunmadığı görülmüştür. Bunun nedeni sera içi ikliminin sera tipini, sera konumun, örtü malzemesine, sera iç hacmine, havalandırma mekanizmasına, ısı perdesi ve gölge tozu kullanımına hatta askıya alma gibi kültürel uygulamalara göre değişmesindendir. Ancak bir bölgede bulunan farklı özellikteki her bir sera için yeni bir eşitlik geliştirilmesi ya da mevcut eşitliklerin kalibre edilmesi mümkün değildir. Bu nedenle kullanılacak ET eşitlikleri bölgede yaygın olarak kullanılan sera tipine göre seçilmesi ve gerekirse bu şartlara göre modifiye edilerek kullanılması önerilmektedir.

Anahtar kelimeler: Aerodinamik direnç, İklimsel veri, Evapotranspirasyon, Referans evapotranspirasyon, Buhar basıncı açığı

Introduction

Feeding problem of increasing population is one of the big challenges of today. However, agricultural land cannot be increased because of soil degradation, erosion and urbanization. According to the fact that it is not possible to increase the agricultural areas proportionally to population growth, it is necessary to obtain higher yield in existing agricultural land (Altıntaş and Akçay 2009). This problem is on a more serious scale in developing countries and requires some measures. Some of these measures are that the use of new technology and agricultural techniques, as well as universalize of greenhouse production (Güllüler 2007).

Greenhouse production activities are being carried out in 1.2 million hectares all over the world. The most of greenhouses areas in the world are based in the Mediterranean basin countries. Spain, Italy and Turkey are at the first three ranks in the presence of greenhouse area among the Mediterranean countries. Spain and Turkey are also at the first two ranks in terms of greenhouse vegetables production (İlbay and Mavi 2015).

Besides, while the amount of water on the earth does not change, the demand for water increases steadily. Some places are self-sufficient in terms of water resources, but some places draw water shortage (Kumbur 2002). It is claimed that there is a significant water shortage in 80 countries having about 40% of the world's population (Hamdy et al. 2003). Particularly in semi-arid and arid areas where water resources are insufficient, the importance of fruitful use of water in the agricultural sector has been ever-increasing (Büyükcangaz and Değirmenci 2002). On the other hand, irrigation is an important input, which provides profitability and sustainability in agriculture. The basic condition for providing the benefit targeted in irrigation is that water should be given at the right time and at the required amount to the plant root zone.

The most important stage for optimum irrigation is the calculation of the evapotranspiration (ET) and the determination of irrigation water requirement. Lysimeters are considered as the most reliable and accurate method for determining the ET. However, they are not preferred by growers because of the difficult, expensive and time-consuming measurement process (Irmak et al. 2003). Otherwise, ET can be estimated by using various measurement and modeling techniques with the help of climatic data (Rana and Katerji 2000). In order to determine the ET, a large number of studies have been conducted in field conditions. For this reason, a large number of ET equations exist based on the climate for field conditions. However, it is more difficult to determine the ET in greenhouses due to environmental and physical variability in the greenhouse conditions. For this reason, there are few studies conducted and improved ET equations on this subject.

There are two different methodologies in greenhouses based on the reference crop and the main crop in order to determine the evapotranspiration by using climatic data. Some researchers used ET equations developed for field conditions directly in greenhouse conditions while some researchers used after modifying them according to greenhouse conditions. Beside of these, there are also some newly developed equations for greenhouse conditions. In this study, 10 different ET equations commonly used to estimate ET based on the climate in greenhouse conditions was examined, reviewed and advantages and disadvantages of the equations are discussed.

Evapotranspiration Equations Based on Reference Crop

In this method, firstly reference crop evapotranspiration (ET_o) value which is occurred from a reference crop (grass or alfalfa) is determined and then this value is multiplied by a coefficient (k_c) developed according to crop and environmental conditions in the growing environment (Eq-1) (Doorenboos and Pruitt 1977; Karaca et al. 2017a).

$$ET_c = ET_0 \, x \, k_c \tag{1}$$

This method is widely used in the field conditions. Some equations with this method have been used in the greenhouse conditions directly, while some of them have been used by modifying according to the greenhouse conditions. Penman, Hargreaves, FAO24-Radiation, Priestley-Taylor, FAO-Penman Monteith and FAO24-Pan Evaporation have been commonly used in the greenhouse.

a-*Penman* (Penman 1948)

Penman equation improved to estimate the evaporation (E) on the open water surface by combining the energy balance method and the aerodynamic method describing the heat transfer between water and air (Eq-2).

$$\lambda E = \frac{\Delta}{\Delta + \gamma}(R_n - G) + K_w \frac{\gamma}{\Delta + \gamma}(a_w + b_w u_2)(e_s - e_a) \tag{2}$$

Where Δ, slope of vapor pressure curve (kPa °C^{-1}); γ, psychometric constant (kPa °C^{-1}); R_n, net radiation at the crop surface (MJ m^{-2} day^{-1}); G, soil heat flux density (MJ m^{-2} day^{-1}); a_w and b_w, the wind function coefficients; u_2, the wind speed (m s^{-1}); λ, the latent heat of vaporization (MJ kg^{-1}), e_s-e_a saturation vapor pressure deficit (kPa).

b-*Hargreaves* (Hargreaves and Samani 1985)

The most important advantage of this equation is that it needed fewer climatic parameter than other equations (Eq-3). This is one of the most preferred equations in order to determine ET_o among equations based on air temperature.

$$ET_o = \left(0.0023\ R_s (T_{max} - T_{min})^{0.5} (T_{mean} + 17.8)\right) / \lambda \qquad (3)$$

Where T_{max}, maximum daily temperature (°C); T_{min}, minimum daily temperature (°C); T_{mean}, mean daily temperature (°C); R_s, solar radiation (MJ m^{-2} g^{-1}); λ, the latent heat of vaporization (MJ kg^{-1}).

c- *FAO24-Radiation* (Doorenboos and Pruitt 1977)

The FAO24-Radiation equation is among the radiation-based methods for determining reference evapotranspiration (Eq-4). This equation is based on energy balance.

$$ET_o = a + b\left(\frac{\Delta}{\Delta + \gamma} R_s\right) \qquad (4)$$

Where R_s, solar radiation (MJ m^{-2} g^{-1}); Δ, slope vapor pressure curve (kPa $°C^{-1}$); γ, psychometric constant (kPa $°C^{-1}$); b, a dimensionless parameter.

d- *Priestley-Taylor* (Priestley and Taylor 1972)

Priestley-Taylor equation is obtained by simplifying Penman equation (Eq-5). In this equation, the aerodynamic component was omitted and assumed that advection was negligible.

$$ET_o = 1.26 \frac{\Delta}{\Delta + \gamma} \frac{R_n - G}{\lambda} \qquad (5)$$

Where Δ, slope of vapor pressure curve (kPa $°C^{-1}$); γ, psychometric constant (kPa $°C^{-1}$); R_n, net radiation at the crop surface (MJ m^{-2} day^{-1}); G, soil heat flux density (MJ m^{-2} day^{-1}); λ, the latent heat of vaporization (MJ kg^{-1}).

e- *FAO-Penman Monteith* (Allen et al. 1998)

Combination-based this equation is accepted as standard by all authorities in field conditions (Eq-6). In greenhouse conditions, while some researchers have used FAO- Penman Monteith equation directly, some researchers have used this equation by modifying.

$$ET_o = \frac{\Delta}{(\Delta + \gamma^*)}(R_n - G) + \frac{\frac{\gamma}{(\Delta + \gamma^*)}(e_s - e_a)(900)u_2}{T_{mean+275}} \qquad (6)$$

Where Δ, slope of vapor pressure curve (kPa $°C^{-1}$); γ^*, modified psychometric constant (kPa $°C^{-1}$); γ psychometric constant (kPa $°C^{-1}$); R_n, net radiation at the crop surface (MJ m^{-2} day^{-1}); G, soil heat flux density (MJ m^{-2} day^{-1}); u_2, long-term mean annual wind speed at 2 m (m s^{-1}) e_s-e_a saturation vapor pressure deficit (kPa); T_{mean}, mean daily temperature (°C).

f- *FAO24-Pan Evaporation* (Doorenboos and Pruitt 1977)

This equation is based on the multiplication of the evaporation value (E_{pan}) measured from the Class-A pan and a pan coefficient value (k_{pan}) which can be changed according to the environmental conditions (Eq-7). This equation is one of the top method for irrigation scheduling in greenhouses.

$$ET_o = E_{pan} \times k_{pan} \qquad (7)$$

Evapotranspiration Equations Based on Main Crop

In these equations, evapotranspiration can be directly determined without the need of a coefficient such as k_c or $k_{pan.}$ These equations have been improved by modifying previously developed equations. The modifications were made by adding various parameters describing plant characteristics to the Penman Monteith equation.

a- *Stanghellini* (Stanghellini 1987)

Stanghellini (1987) revised the Penman-Monteith (Monteith 1965) equation by adding new parameters to better describe the greenhouse and crop system (Eq-8). These new parameters are obtained from internal and external resistances of the plant by taking into account the greenhouse climate and wind speed. Crop canopy is defined to include the top and bottom surfaces of the leaf.

$$ET = 2LAI\,\frac{1}{\lambda}\left[\frac{s(R_n - G) + K_t[VPD\,\rho\,C_p]}{s + \gamma[1 + r_c/r_a]}\right]$$

$$R_n = \frac{0.07R_{ns} - 252\rho\,C_p(T - T_0)}{r_R} \tag{8}$$

$$r_R = \frac{\rho C_p}{4\sigma(T + 273.15)^3}$$

Where, ET_o, Reference evapotranspiration (mm day^{-1}); R_n Net radiation at the crop surface (MJ m^{-2} day^{-1}); G, Soil heat flux density (MJ m^{-2} day^{-1}); K_t Unit conversion factor equal to 3600 s h^{-1}; VPD, Daily or hourly vapor pressure deficit (kPa); ρ, Mean air density (kg m^{-3}); C_p, Specific heat of the air (MJ kg^{-1} °C^{-1}); r_R, Radiative resistance (s m^{-1}); r_c, Canopy resistance (s m^{-1}); r_a; Aerodynamic resistance (s m^{-1}); λ, Latent heat of vaporization (MJ kg^{-1}); s, Slope of the saturation vapor pressure curve (kPa °C^{-1}); γ, Psychrometric constant (kPa °C^{-1}); R_{ns}, Net short wave radiation (MJ m^2 day^{-1}); R_s, Ground level solar radiation (MJ m^2 day^{-1}); T, Hourly or daily mean air temperature (°C); T_o, Leaf temperature (°C); σ, Stefan-Boltzman constant (MJ m^{-2} K^{-4} day^{-1}); LAI, Leaf area index (m^2 m^{-2}).

b- *Fynn* (Fynn et al. 1993)

Although this model shows similarity with the Stanghellini equation, the solar radiation and the heat flux calculation used by Stanghellini is not being included in this model (Eq-9). Fynn et al. (1993) supposed that the leaf and air temperatures were equal to simplify the required measurements (Ilahi 2009).

$$ET = \frac{2LAI\,\rho\,C_p\,(e_s - e_a)/r_e + \delta(R_n - G)}{\lambda\,\gamma\,r_i} \tag{9}$$

Where, R_n, net radiation at the crop surface (J m^{-2} s^{-1}); G, soil heat flux density (J m^{-2} s^{-1}); ρ, mean air density (kg m^{-3}); C_p, specific heat of the air (J kg^{-1} °C^{-1}); e_s, Saturation vapor pressure at mean air temperature (Pa); e_a, vapor pressure of the air (Pa); λ, latent heat of vaporization (J kg^{-1}); γ, psychrometric constant (Pa °C^{-1}); δ, Slope of saturated vapor pressure curve with temperature (Pa°C^{-1}); r_e, external resistance of canopy to sensible heat (s m^{-1}); r_i, internal resistance of canopy to vapor transfer (s m^{-1}); LAI, Leaf area index (m^2 m^{-2}).

c-*Takakura* (Takakura et al. 2009)

This equation is also known as a heat balance method (Eq-10). Takakura et al. (2009) have reported that this equation is simpler and more accurate than FAO-Penman Monteith equation.

$$ET = R_n - h(T - T_w) \tag{10}$$

Where, ET, crop evapotranspiration rate (W m^{-2}); R_n, net radiation above canopy (W m^{-2}); h, convective heat transfer coefficient of air (7 W m^{-2} °C^{-1}); T, temperature of the air (°C^{-1}); T_w, temperature of the evaporative surface.

d- *Simplified Model* (Baille et al. 1994)

Baille et al. (1994) proposed an equation that relates evapotranspiration to G, D and LAI, based on the formalism of the Penman-Monteith equation (Eq-11).

$$ET = A\ f_1\ G + B\ f_2\ D$$

$$f_1 = 1 - \exp(-\alpha LAI) \qquad f_2 = LAI \qquad (11)$$

$$A = \frac{\Delta}{\Delta + \gamma^*} \qquad B = \frac{3.6x10^3 \rho\ C_p/r_a}{\lambda(\Delta + \gamma^*)}$$

Where, ET, crop evapotranspiration rate (kg m^{-2} h^{-1}); G, inside solar radiation (kg m^{-2} h^{-1}); D, inside air vapor pressure deficit (kPa); LAI, Leaf area index (m^2 m^{-2}); f1, f2 dimensionless functions of LAI (m^2 m^{-2}); A, values of model parameter (dimensionless); B, values of model parameter (kg m^{-2} h^{-1} kPa^{-1}); α, Leaf angle distribution (0.64 from Stanghellini (1987)); Δ, slope of the saturated vapor pressure-temperature curve (kPa K^{-1}); $\gamma^* = (1 + r_s/r_b)$, γ^* is the psychometric constant (kPa K^{-1}); r_s, canopy surface resistance (s m^{-1}); r_b, canopy boundary layer resistance (s m^{-1}); λ, latent heat of vaporization (J kg^{-1}); ρ, Density of air (kg m^{-3}); C_p Specific heat of air (J kg^{-1} K^{-1}); r_a, leaf aerodynamic resistance (s m^{-1}).

Assessment of the Equations

Although there were not many studies conducted to determine ET in greenhouse conditions, it was seen in the literature that the most accurate method was the lysimeter method based on the soil-water balance approach (Stanghellini 1987; Fynn et al. 1993; Möller and Assouline 2007; López-Cruz et al. 2008; Fernández et al. 2010). The difficult, expensive and longtime requirement of the lysimeter method plays an important role in the preference of the equations based on climate to determine ET. Estimating ET using equations based on climate has been widely used application today. For this reason, a large number of equations based on different methods (based on temperature, radiation, mass transfer, pan evaporation and combination) have been developed (Karaca et al. 2017b). It is sufficient to know the relationship between the soil-plant and the atmosphere for estimating ET in field conditions. However, the relationship between greenhouse type, greenhouse cover, greenhouse climate, ventilation conditions, plant and soil should be examined in detail in greenhouse conditions. All these changes are directly related to ET, as they affect temperature, humidity, wind and radiation distribution within the greenhouse. Indeed, Jolliet and Bailey (1992) reported that 1 MJ m^{-2} day^{-1} increase in the amount of solar radiation increased ET of young plant by 0.09 mm day^{-1}; 0.1 kPa increase in vapor pressure deficit increased ET by 0.013 mm day^{-1}; 1 m s^{-1} increase in air movement increased ET by 0.13 mm day^{-1}. For this purpose, Ilahi (2009) has classified greenhouses in three categories as low, medium and high-tech greenhouses.

Gavilán et al. (2015) reported that there was no standard method in order to determine ET for greenhouse crops. However, the model which was the worldwide most widely used and accepted as a standard for determining plant water consumption was the FAO methodology (FAO adaptation of the Penman-Monteith equation) based on reference evapotranspiration (ET_o) and plant coefficient (k_c) (Katerji et al. 2008). Some researchers (Orgaz et al. 2005; Fernández et al. 2010) also tried the same methodology in greenhouse conditions. It is important that ET_o and k_c values are accurately determined for a more precision ET estimate in greenhouse conditions. Orgaz et al. (2005) determined the k_c coefficients of a large number of single-year greenhouse plants cultivated in low-tech greenhouses on the Mediterranean coast of Spain. However, since the k_c value was also influenced by cultural processes such as greenhouse type, growing season, planting density and hanging, it should be specially developed for each region.

Transpiration models for greenhouses were first developed in Europe and North America for some vegetable cultivars such as tomatoes (Stanghellini 1987; Jolliet and Bailey 1992), cucumber (Yang et al. 1990), lettuce (Pollet et al. 1999). In these regions of the northern latitudes, ventilation of glass greenhouses is rarely needed in most of the growing season. For this reason, the boundary layer conductivity of plants growing in glasshouses tends to be much smaller than expected for similar plants growing in open field conditions (Katsoulas and Kittas 2011). Conversely, the greenhouse plant transpiration in regions having a Mediterranean Climate or warm regions having similar climate is much more dependent on convection. Because the ventilation and turbulence are strong, the saturation deficit of the leaf surface is closely related to the saturation deficit of the air and finally, it is directly influenced by the saturation deficit outside the greenhouse (Boulard and Wang 2000).

It was understood from previous studies (Orgaz et al. 2005; Möller and Assouline 2007; Fernández et al. 2010) that the amount of evapotranspiration in the greenhouse was less than outside the greenhouse. Researchers reported that the reason for this caused from significantly decrease (up to 56% of seasonal open field conditions) of solar radiation as well as lower wind speed inside the greenhouse. They also explained that the shading dust and thermal curtains applied in the spring and summer months, reduces the solar radiation value in the greenhouse.

A large number of climatic parameters were needed for accurate ET estimation with climate-based equations. However, it could be difficult to obtain this climate data by farmers. For this reason, some researchers studied to estimate the amount of ET inside the greenhouse using climatic data belong to outside greenhouse. Valdés-Gómez et al. (2009) made irrigation scheduling of tomato crop with Priestley-Taylor model by using solar radiation values from outside the greenhouse. In the study, ET was estimated at 6.1% error.

Prenger et al. (2002) compared Penman, FAO- Penman-Monteith, Stanghellini and Fynn models with lysimeter measurements for estimating ET inside greenhouse of Red Sunset red (Acer Rubrum 'Red Sunset') maple trees in high-tech greenhouses. The researchers reported that the equations which makes the most accurate assumption were Stanghellini equation (r^2=0.958) and Fynn (r^2=0.940), FAO Penman-Monteith (r^2=0.886) and FAO Penman (r^2=0.872) equations followed these. It was reported that Penman and FAO-Penman-Monteith equations estimate ET value too much in this study. Likewise, Pamungkas et al. (2014) reported that the most suitable ET equation for tomato plants grown in soilless culture was Stanghellini equation.

Chartzoulakis and Drosos (1995) and Fernández et al. (2010) were determined ET_o value by using FAO24-Pan evaporation method in Mediterranean climate conditions. Fernández et al. (2010) recommend that the pan coefficient (k_{pan}) must be 0.79 and 0.77, respectively, in plastic greenhouses where shading dust was used and not used. Zeng et al. (2009) reported that k_{pan} coefficient could be taken 1.0 in greenhouses grown with cucumber. Ucar et al. (2011) reported that k_{pan} coefficient could be taken 1.0 in greenhouses grown carnation irrigated one-day interval.

When previous studies were examined, it was seen that some researchers (Boulard and Wang 2000; Orgaz et al. 2005; Liu et al. 2008) used the canopy aerodynamic resistance which was a parameter of Penman Monteith equation as 70 s m^{-1} which was recommended by Allen et al. (1998). However, Fernández et al. (2010) suggested that this value should be used as 150 s m^{-1} especially in Mediterranean conditions and then they corrected this value as 295 s m^{-1}. Baille et al. (1994) determined the ET of nine different ornamental plants growing in pots in the high-tech greenhouse with simplified model and compared with the direct measurement values which were obtained by weighing the pots. They determined that high correlation (r^2=0.87-0.97) by obtaining solar radiation and vapor pressure deficit (VPD) inside the greenhouse.

Takakura et al. (2009) determined ET values of tomato plants with energy balance method and then compared with measured values. As a result of the study, they stated that the ET values calculated by the energy balance method were in good agreement with the measured values and that the equation was simple and suitable for irrigation control in the greenhouse.

Liu et al. (2008) identified ET_o values by using five different equations (Priestley-Taylor, FAO24-Radiation, Hargreaves, Penman and FAO-Penman Monteith) with the help of micrometeorological data from the glasshouse where grown banana. The ET_c values obtained by multiplying the ET_o values by the plant coefficient were compared directly with the measured values. Researchers reported that ET_o values are more dependent on vapor pressure deficit and air temperature in the greenhouse. Therefore, ET_o equations based on temperature and humidity measurements in naturally ventilated greenhouses would yield better results. As a result of the study, it was seen that VPD and temperature inside the greenhouse had the linear correlations (r^2) with ET being a correlation coefficient of 0.67 and 0.62, respectively. The highest determination coefficient (r^2=0.67) among the equations were found in Penman equation. FAO- Penman Monteith equation (r^2=0.63), FAO-Radiation equation (r^2=0.52), Hargreaves equation (r^2=0.49) and Priestley-Taylor equation (r^2=0.47) followed this equation, respectively.

Fernández et al. (2010) determined the evapotranspiration (ET_o) with five different equations (FAO-Penman Monteith, FAO24-Penman, FAO24-Radiation and FAO24-Pan and Hargreaves) from the grass (*Cynodon dactylon* L.) grown in a low-tech greenhouse in Mediterranean climates and compared with the values obtained from the lysimeter. The best correlations were found FAO24-Pan (r^2=0.98, RMSE=0.34), FAO24-Penman (r^2=0.98, RMSE=0.36), FAO-Radiation (r^2=0.97, RMSE=0.45), Hargreaves (r^2=0.97, and FAO-Penman Monteith (r^2=0.97, RMSE=0.56), respectively.

Villarreal-Guerrero et al. (2012) compared the ET values obtained from three different ET equations (Stanghellini, Penman-Monteith and Takakura) with ET obtained from sap flow meter in different ventilation types (natural ventilation with fog cooling and mechanical ventilation with pad and fan) and different growing season (spring, summer, fall). Researchers reported that Stanghellini equation gave the most accurate results in all conditions, but statistically (α=0.05) was not different from other equations. They stated that these three models could be also used by incorporating to climate control strategy of greenhouse.

Conclusion

In this study, it was aimed to determine ET equations which were developed based on climatic data in greenhouse conditions and to compile the studies about these equations. The estimating equations for ET in the greenhouse were examined in two different ways, based on the reference crop and the main crop. It was seen that there was a small number of studies and equations developed in greenhouse conditions, unlike field conditions. In addition, it has been observed that the equations developed for field conditions have been tested in the greenhouse conditions in various studies.

It was seen from the studies that while there was a standard equation of estimating ET based on climatic data in field conditions, there was no standard equation in the greenhouse conditions. Equations developed for field conditions in a region can be used in another region having the same climate directly or with some special calibration. However, calibration in greenhouse conditions must be done not only specific to the region but also according to the types of the greenhouses widely used in the region, the ventilation mechanism, the greenhouse direction, the volume of greenhouse, the cultural processes applied to plants such as shade dusting and hanging. Some researchers identified ET values inside the greenhouse by using climate data measured outside the greenhouse. Some researchers reported that the amount of ET could be determined more sensitive by accurately determining the value of plant canopy aerodynamic resistance.

Previous studies indicated that Stanghellini and Fynn equations estimated the ET value with high accuracy in fully equipped modern greenhouses while with low accuracy in the low-tech greenhouses in the Mediterranean climate. In addition, the requirement for numerous climatic parameters of the equations restricted the usage on the farmers. For this reason, it was seen that the use of the equations based on reference crop in hot regions was more common. It was understood that the use of Class-A Pan was very widespread in greenhouse conditions as well as in field conditions and the pan coefficient was determined for many regions and crops.

References

Allen RG, Pereira LS, Raes D, Smith M (1998). Crop evapotranspiration: Guidelines for computing crop water requirements. FAO, Roma, 300 pp.

Altıntaş G, Akçay Y (2009). Arazi toplulaştırması uygulamalarında üreticilerin toplulaştırmaya bakış açılarını etkileyen faktörler. Tarım Ekonomisi Dergisi 15(1): 35–43.

Baille M, Baille A, Laury JC (1994). A simplified model for predicting evapotranspiration rate of nine ornamental species vs. climate factors and leaf area. Scientia Horticulturae 59(3–4): 217–232.

Boulard T, Wang S (2000). Greenhouse crop transpiration simulation from external climate conditions. Agricultural and Forest Meteorology 100(1): 25–34.

Büyükcangaz H, Değirmenci H (2002). Drenaj sularının sulamada yeniden kullanılması. Su Havzalarında Toprak ve Su Kaynaklarının Korunması, Geliştirilmesi ve Yönetimi Sempozyumu-Antakya : 614–617.

Chartzoulakis K, Drosos N (1995). Water use and yield of greenhouse grown eggplant under drip irrigation. Agricultural Water Management 28(2): 113–120.

Doorenboos J, Pruitt WO (1977). Guidelines for predicting crop water requirements, irrigation and drainage paper 24. Land and Water Development Division FAO Rome 24: 144.

Fernández MD, Bonachela S, Orgaz F, Thompson R, López JC, Granados MR, Gallardo M, Fereres E (2010). Measurement and estimation of plastic greenhouse reference evapotranspiration in a Mediterranean climate. Irrigation Science 28(6): 497–509.

Fynn RP, Alshooshan A, Short TH, McMahon RW (1993). Evapotranspiration measurement and modeling for a potted chrysanthemum crop. Transactions of the Asae 36(6): 1907–1913.

Gavilán P, Ruiz N, Lozano D (2015). Daily forecasting of reference and strawberry crop evapotranspiration in greenhouses in a Mediterranean climate based on solar radiation estimates. Agricultural Water Management 159: 307–317.

Güllüler F (2007). Adana ili ve ilçelerindeki seraların yapısal özelliklerinin incelenmesi ve t.s.e standartlarına uygunluğunun araştırılması. ÇÜ Fen Bilimleri Enstitüsü Tarımsal Yapılar ve Sulama Anabilim Dalı Yüksek Lisans Tezi, Adana : 86.

Hamdy A, Ragab R, Scarascia-Mugnozza E (2003). Coping with water scarcity: Water saving and increasing water productivity. Irrigation and Drainage. pp 3–20.

Hargreaves G., Samani Z. (1985). Reference crop evapotranspiration from temperature. Applied Engineering in Agriculture 1(2): 96–99.

Ilahi WFF (2009). Evapotranspiration models in greenhouse. master thesis-agricultural and bioresearch engineering at wageningen university, The Netherlands : 52

İlbay E, Mavi F (2015). TR63 Bölgesi Seracılık (Örtüaltı Bitki Yetiştiriciliği) Sektör Raporu. TC Doğu Akdeniz Kalkınma Ajansı : 59.

Irmak S, Irmak A, Allen RG, Jones JW (2003). Solar and net radiation-based equations to estimate reference

evapotranspiration in humid climates. Journal of Irrigation and Drainage Engineering 129(5): 336–347.
Jolliet O, Bailey BJ (1992). The effect of climate on tomato transpiration in greenhouses: measurements and models comparison. Agricultural and Forest Meteorology 58(1–2): 43–62.
Karaca C, Büyüktaş D, Baştuğ R, Aydinşakir K, Tekelioğlu B (2017a). Antalya koşullarında kıyas bitki su tüketiminin alansal ve zamansal dağılımının belirlenmesi. Derim 2017(34): 158–171.
Karaca C, Tekelioğlu B, Büyüktaş D, Baştuğ R (2017b). Assessment of the equations computing reference crop evapotranspiration. Academia Journal of Engineering and Applied Sciences ICAE-IWC(Special Issue): 144–161.
Katerji N, Mastrorilli M, Rana G (2008). Water use efficiency of crops cultivated in the Mediterranean region: Review and analysis. European Journal of Agronomy 28(4): 493–507.
Katsoulas N, Kittas C (2011). Greenhouse crop transpiration modelling. Evapotranspiration - From Measurements to Agricultural and Environmental Applications : 312–328.
Kumbur H (2002). Dünya, Türkiye, Ortadoğu ülkelerinde su potansiyeli ve karşılaşılan sorunlar. Su Havzalarında Toprak ve Su Kaynaklarının Korunması, Geliştirilmesi ve Yönetimi Sempozyumu : 193–202.
Liu HJ, Cohen S, Tanny J, Lemcoff JH, Huang G (2008). Estimation of banana (Musa sp.) plant transpiration using a standard 20 cm pan in a greenhouse. Irrigation and Drainage Systems 22(3–4): 311–323.
López-Cruz IL, Olivera-López M, Herrera-Ruiz G (2008). Simulation of greenhouse tomato crop transpiration by two theoretical models. Acta Horticulturae (797): 145–150.
Möller M, Assouline S (2007). Effects of a shading screen on microclimate and crop water requirements. Irrigation Science 25(2): 171–181.
Monteith JL (1965). Evaporation and Environment. Symposia of the Society for Experimental. Biology 19: 205-234.
Orgaz F, Fernández MD, Bonachela S, Gallardo M, Fereres E (2005). Evapotranspiration of horticultural crops in an unheated plastic greenhouse. Agricultural Water Management 72(2): 81–96.
Pamungkas AP, Hatou K, Morimoto T (2014). Evapotranspiration model analysis of crop water use in plant factory system. Environmental Control in Biology 52(3): 183–188.
Penman HL (1948). Natural Evporation from Open Water, Bare Soil and Grass. The Royal Society 193(1032): 120–145.
Pollet S, Bleyaert P, Lemeur R (1999). Calculating the evapotranspiration of head lettuce by means of the penman-monteith model. Bet Dagan, 1999.
Prenger JJ, Fynn RP, Hansen RC (2002). A Comparison of four evapotranspiration models in a greenhouse environment. Transactions of the ASAE 45(6): 1779–1788.
Priestley C, Taylor R (1972). On the assessment of surface heat flux and evaporation using large-scale parameters. Monthly Weather Review 100(2): 81–92.
Rana G, Katerji N (2000). Measurement and estimation of actual evapotranspiration in the field under Mediterranean climate: A review. European Journal of Agronomy. pp 125–153.
Stanghellini C (1987). Transpiration of greenhouse crops an aid to climate management. Wageningen University, 150 pp.
Takakura T, Kubota C, Sase S, Hayashi M, Ishii M, Takayama K, Nishina H, Kurata K, Giacomelli GA (2009). Measurement of evapotranspiration rate in a single-span greenhouse using the energy-balance equation. Biosystems Engineering 102(3): 298–304.
Ucar Y, Kazaz S, Askin MA, Aydinsakir K, Kadayifci A, Senyigit U (2011). Determination of irrigation water amount and interval for carnation (Dianthus caryophyllus L.) with pan evaporation method. HortScience 46(1): 102–107.
Valdés-Gómez H, Ortega-Farías S, Argote M (2009) Evaluation of the Water Requirements for a Greenhouse Tomato Crop using the Priestley-Taylor Method . Chilean Journal of Agricultural Research 69(1): 3–11.
Villarreal-Guerrero F, Kacira M, Fitz-Rodríguez E, Linker R, Kubota C, Giacomelli GA, Arbel A (2012). Simulated performance of a greenhouse cooling control strategy with natural ventilation and fog cooling. Biosystems Engineering 111(2): 217–228.
Yang X, Short TH, Fox RD, Bauerle WL (1990). Transpiration, leaf temperature and stomatal resistance of a greenhouse cucumber crop. Agricultural and Forest Meteorology 51(3–4): 197–209.
Zeng CZ, Bie ZL, Yuan BZ (2009). Determination of optimum irrigation water amount for drip-irrigated muskmelon (Cucumis melo L.) in plastic greenhouse. Agricultural Water Management 96(4): 595–602.