ASSESSMENT OF EVAPOTRANSPIRATION ACCURACY CALCULATED OF SOME VEGETABLES BY AERODYNAMIC RESISTANCE DETERMINED BASED ON WIND SPEED, PLANT HEIGHT, AND VEGETATION COVER UNDER GREENHOUSE CONDITIONS

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ABSTRACT

This study aimed to compare the evapotranspiration (ET) estimates obtained from lysimeters and the energy balance method for crops grown in greenhouses under Mediterranean conditions. The aerodynamic resistance (r_a) in the energy balance equation was determined using the Brutsaert and Stricker and Perrier methods, specifically developed for field conditions. Lysimeters were used to measure the actual ET values, and these were compared with the ET estimates obtained using the energy balance method. This research focused on four greenhouse crops: tomatoes, eggplants, peppers, and cucumbers. The research was conducted in a randomized complete block design during the autumn of 2018 and the spring of 2019. The estimated ET with energy balance oscillated between -13555 (W m^{-2}) and 148121 (W m^{-2}), especially on days when the ventilation was closed. Therefore, these models were not suitable for Mediterranean type plastic greenhouses with natural ventilation. The Brutsaert and Stricker (1979) and Perrier (1975) methods were also not suitable for accurately predicting ET in the studied greenhouse crops. In particular, the aerodynamic resistance values calculated from the energy balance equation led to erroneous ET estimates under natural ventilation conditions.

Keywords: ET, Lysimeter, Mediterranean, r_a

INTRODUCTION

The determination of evapotranspiration (ET), which represents the efficient transport of water vapor between crops and the atmosphere, is of significant importance in agricultural, hydrological, and environmental sciences. ET estimation involves various measurement and modeling techniques, either simulating ET as a biophysical process or calculating it directly or indirectly through empirical methods (Rana and Katerji, 2000). However, the complexity levels of these techniques and models vary.

Micrometeorological methods, which are physically based and utilize the laws of thermodynamics, play a prominent role in ET estimation (Lazzara and Rana 2010). The widely used Penman-Monteith equation is based on the assumption that the plant canopy

surface can be reduced to that of a "big leaf" (Alves et al., 1998). This equation effectively integrates the physical and biophysical constraints in the plant into a single simple equation for ET estimation (Monteith and Unsworth, 2013), considering that the primary transpiration process occurs in the stomatal pores beneath the "big leaf."

Aerodynamic resistance (r_a) refers to the resistance against the upward movement of water vapor due to friction between the plant surface and airflow (Monteith, 1965). Various approaches have been developed for calculating r_a, some based on equations that consider the wind speed, plant height, and canopy distribution, while others use dimensionless groups to determine ra from the heat transfer coefficient. Alternatively, r_a can be obtained by reverse solving the energy balance equation. Some studies (Bailey et al., 1993; Gong et al., 2017; Jolliet and Bailey, 1992) suggested using a constant value for r_a in ET estimation.

Under field conditions, r_a was calculated using a model that describes the turbulent transport of water vapor between leaves and the atmosphere. Numerous studies have highlighted the relationship between aerodynamic resistance and wind speed as well as plant roughness (Allen et al., 1998; Alves et al., 1998; Kjelgaard and Stockle, 2001).

However, when the wind speed is close to zero, the r_a value obtained using this method tends to approach infinity. For instance, Fernández et al. (2010) reported that the daily wind speed values measured in a greenhouse mostly ranged from 0.01 to 0.2 m/s, leading to r_a values fluctuating between 2,080 and 20,800 s m^{-1}. Therefore, caution must be exercised when applying this method under low-wind-speed conditions, particularly for measurements within greenhouses. On the other hand, some researchers (Gong et al., 2017) have pointed out that aerodynamic resistance can be modified and utilized in greenhouses equipped with ventilation systems, where the wind speed is higher than that of naturally ventilated greenhouses.

This study aimed to compare the evapotranspiration values of different greenhouse vegetables using two different methods. In the first method, evapotranspiration was determined directly using a lysimeter, whereas, in the second method, known as the energy balance method, evapotranspiration was estimated based on calculated aerodynamic resistance values considering factors such as wind speed, plant height, and vegetation cover. By conducting this comparison, this study aims to determine the effectiveness and accuracy of the aerodynamic resistance method in assessing evapotranspiration.

MATERIALS AND METHOD

The study was conducted at the Agricultural Research and Application Field of Akdeniz University in Antalya, Turkey, located between 30° 38' 30" - 30° 39' 45" east longitudes and 36° 53' 15" - 36° 54' 15" north latitudes, during two different growing periods: the fall season from September 14, 2018, to February 22, 2019, and the spring season from March 01, 2019, to July 15, 2019.

In this study, irrigation water of the C2S1 quality class, sourced from a pumping system located at the Agricultural Research and Application Field of Akdeniz University, was used. The soil had a silty clay loam texture with field capacity (FC), permanent wilting point (WP), and bulk density (As) values of 30.8% (Pw%), 14.1% (Pw%), and 1.38 (g cm^{-3}), respectively.

In the study, the lysimeters, in which the plants were grown, were positioned in three replications following a randomized complete block design along different orientations of the

greenhouse. The plant materials selected for this study were varieties commonly cultivated in Antalya and its surrounding regions, which are suitable for both autumn and spring cultivation. The following varieties were chosen: Anıt F1 for tomatoes, Ayda F1 for cucumbers, Corsica for eggplants, and Buket for peppers.

The greenhouse used in this study represents the common greenhouse type in the region, featuring a gothic roof structure with a plastic (PE) covering. The greenhouse measures 9.6 meters in width, 25 m in length, 4 m in sidewall height, and 6 m in ridge height. The covering material consists of a widely used 175 µm transparent UV + IR + EVA + AD additive-coated polyethylene (PE) film with a durability of 36 months. Inside the greenhouse, there were 12 drainage-type lysimeters, each measuring 1.85×2.70 meters and having a depth of 0.6 meters.

The internal climate of the greenhouse was continuously monitored using a meteorology station positioned at the center of the greenhouse, at a height of 1.5 meters above the ground, with data collected at 5-minute intervals. The meteorological station was equipped with various sensors, including an air temperature sensor (PT100 1/3 Class B, Pessl Instruments, Weiz, Austria), relative humidity sensor (Rotronic hygrometer IN-1, Pessl Instruments, Weiz, Austria), pyranometer (LI-200SZ, Pessl Instruments, Weiz, Austria), and net radiation sensor with all its components (CNR4, Kipp&Zonen, Delft, Netherlands). The data from the net radiation sensor were recorded using a model CR1000X data logger (Campbell Scientific, Inc., Utah, USA), while all other recorded data were collected using an iMETOS 3.3 data logger (Pessl Instruments, Weiz, Austria). The climatic data outside the greenhouse were obtained from the station of the Turkish State Meteorological Service, located at a latitude of 36° 53’ N and longitude of 30° 38’ E. The distance between the external meteorological station and the greenhouse was approximately 0.3 kilometers.

Owing to the limitations of mechanical anemometers, such as their starting threshold and partial directional response, sonic anemometers are widely recognized as the most suitable devices for measuring air movement inside greenhouses (Wang et al., 1999). Consequently, a sonic anemometer was employed to measure the wind speed within the greenhouse. The DS-2 ultrasonic anemometer (DecagonDevices, Pullman, USA) is a research-grade two-dimensional sensor specifically designed for agricultural, forestry, and environmental research applications. It offers a sensitivity of 0.01 m/s, making it ideal for measuring wind speed in areas with lower air velocities, such as inside greenhouses and around plant canopies, where mechanical wind sensors (cup anemometers) cannot accurately measure wind speed. An infrared thermometer (Fluke 568, Fluke Corporation, Everett, USA) with an accuracy of 1% was used to determine plant canopy temperature. Plant temperatures were measured after adjusting for the specific emissivity values of each plant species. These emissivity values were obtained from a study conducted by (López et al., 2012), who reported values of 0.983 for tomatoes, 0.978 for peppers, 0.983 for cucumbers, and 0.973 for eggplants. Consequently, the emissivity value of the infrared thermometer was set to 0.98 based on these plant-specific values.

The determination of irrigation water applied to lysimeters was based on Equation 1:

$$I = \frac{P_{v(FC)} - P_{v(AW)}}{100} Dx\ A\ x\ P \quad (1)$$

In this equation, I is the quantity of irrigation water applied (L); $P_{v(FC)}$ is the field capacity of the soil (%); $P_{v(AW)}$ is the available water content of the soil (%); D is the depth of the soil (mm); A is the surface the area of the lysimeters (m^2); and P is the wetted percentage of soil (%).

The ET was determined on a weekly basis using the following water budget equation (Equation 2) (Fernández et al., 2010; Orgaz et al., 2005).

$$ET = (SWC_{t0} - SWC_{t1}) + IR - D_r \quad (2)$$

ET is the measured evapotranspiration between two measurement dates (mm); SWCto-SWCt1 is the change in soil water content between the two measurement dates (mm); IR represents the applied irrigation water amount (mm); and Dr is the amount of drainage water (mm)

The energy balance method, as given in Equation 3, was used for the indirect estimation of ET.

$$\lambda E = R_n - G - \frac{\rho_a c_p (T_c - T_a)}{r_a} \quad (3)$$

In the equation, λE is the latent heat flux (W m^{-2}); R_n is the net radiation (W m^{-2}); G is the soil heat flux (W m^{-2}); is the air density (kg m^{-3}); cp is the specific heat of air (J kg^{-1} K^{-1}); T_c is the plant canopy temperature (K); T_a is the air temperature (K); and r_a is the aerodynamic resistance (s m^{-1}).

The r_a was calculated using the methods of Brutsaert and Stricker (1979) (Equation 4) and Perrier (1975) (Equation 5) based on parameters such as wind speed, plant height, and plant canopy characteristics.

$$r_a = \frac{ln\left[\frac{z_r - d_u}{z_{om}}\right] ln\left[\frac{z_h - d_u}{z_{oh}}\right]}{k^2 u_z} \quad (4)$$

$$r_a = \frac{ln\left[\frac{z_r - d_u}{h_c - d_u}\right] ln\left[\frac{z_h - d_u}{z_{om}}\right]}{k^2 u_z}$$

$$d_u = 0.67 h_c \quad (5)$$

$$z_{om} = 0.13 h_c$$

$$z_{oh} = 0.1 z_{om}$$

In the equations, r_a is the aerodynamic resistance (s m^{-1}); z_r is the height of wind measurements (m); du is the zero-plane displacement (m); z_{om} is the roughness length governing momentum transfer (m); z_h is the height of relative humidity measurements (m); z_{oh} is the roughness length governing the transfer of heat and vapor (m); h_c is the plant height (m); k is the von Karman's constant (0.41); and u_z is the wind speed at height z (m s^{-1}).

The plotted figures and analyses were generated using OriginPro v2023a (OriginLab Corporation, MA, USA) software to assess the temporal fluctuations in the measured and predicted ET values.

RESULTS AND DISCUSSION

The ET values obtained by using the ra values calculated through the Brutsaert and Stricker (1979) and Perrier (1975) methods, as incorporated in the energy balance equation, were given in Figures 1 and 5 for tomato plants, Figures 2 and 6 for eggplant plants, Figures 3 and 7 for pepper plants, and Figures 4 and 8 for cucumber plants.

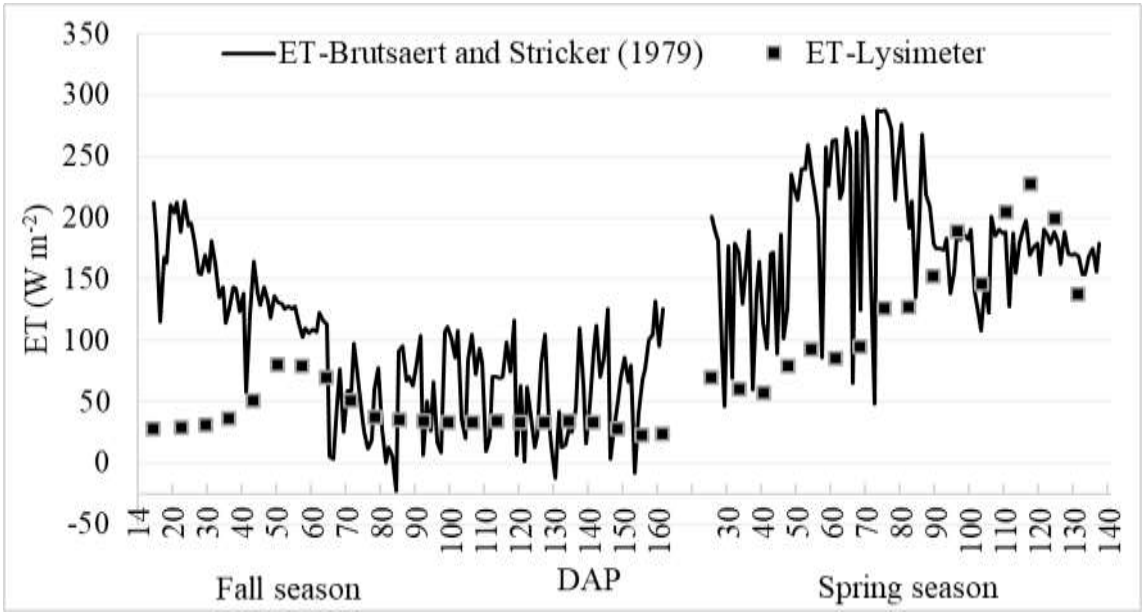


Figure 1. Comparison of ET values of tomato using the energy balance method calculated by the Brutsaert and Stricker (1979) equation and direct lysimeter measurements. *ET is the evapotranspiration and DAP is the days after planting*

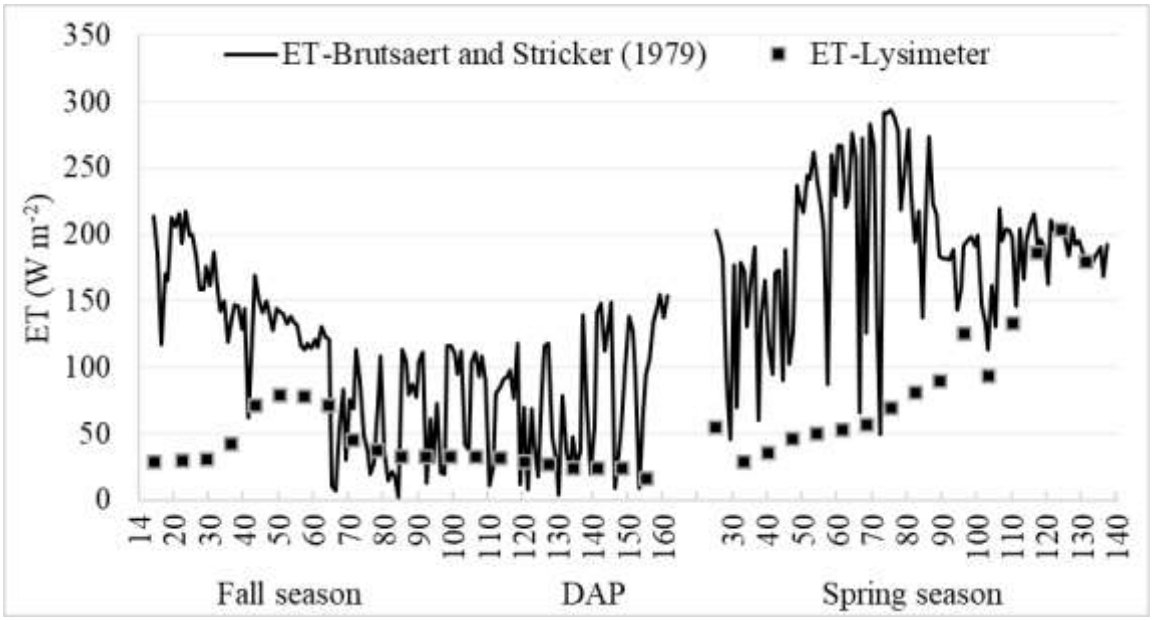


Figure 2. Comparison of ET values of eggplant using the energy balance method calculated by the Brutsaert and Stricker (1979) equation and direct lysimeter measurements. *ET is the evapotranspiration and DAP is the days after planting*

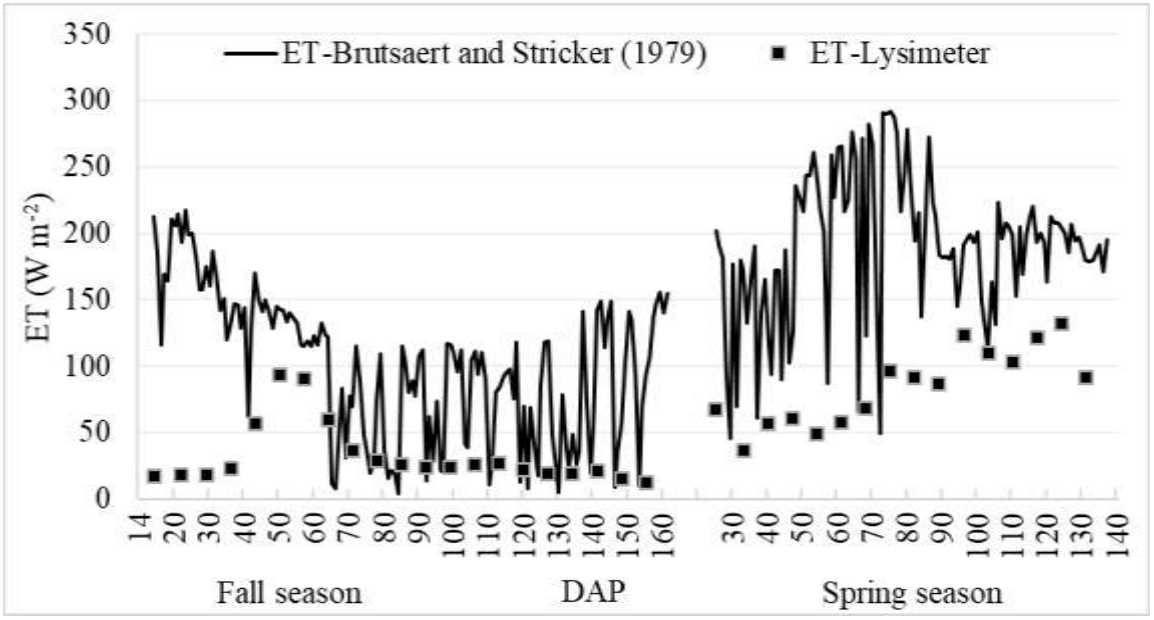


Figure 3. Comparison of ET values of pepper using the energy balance method calculated by the Brutsaert and Stricker (1979) equation and direct lysimeter measurements. *ET is the evapotranspiration and DAP is the days after planting.*

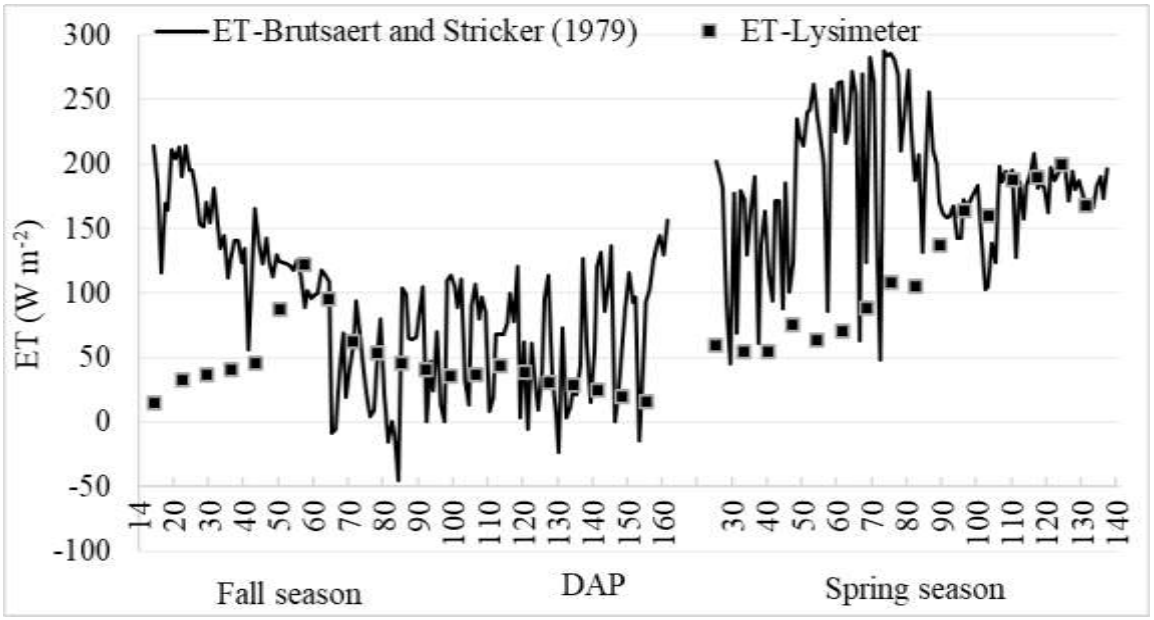


Figure 4. Comparison of ET values of cucumber using the energy balance method calculated by the Brutsaert and Stricker (1979) equation and direct lysimeter measurements. *ET is the evapotranspiration and DAP is the days after planting.*

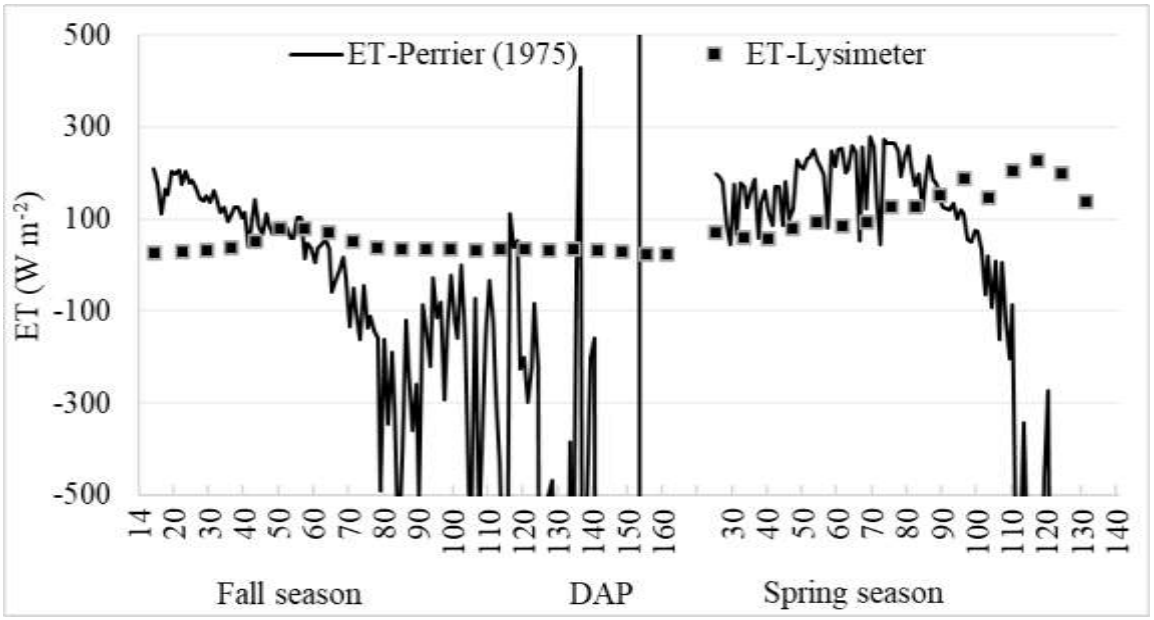


Figure 5. Comparison of ET values of tomato using the energy balance method calculated by the Perrier (1975) equation and direct lysimeter measurements. *ET is the evapotranspiration and DAP is the days after planting.*

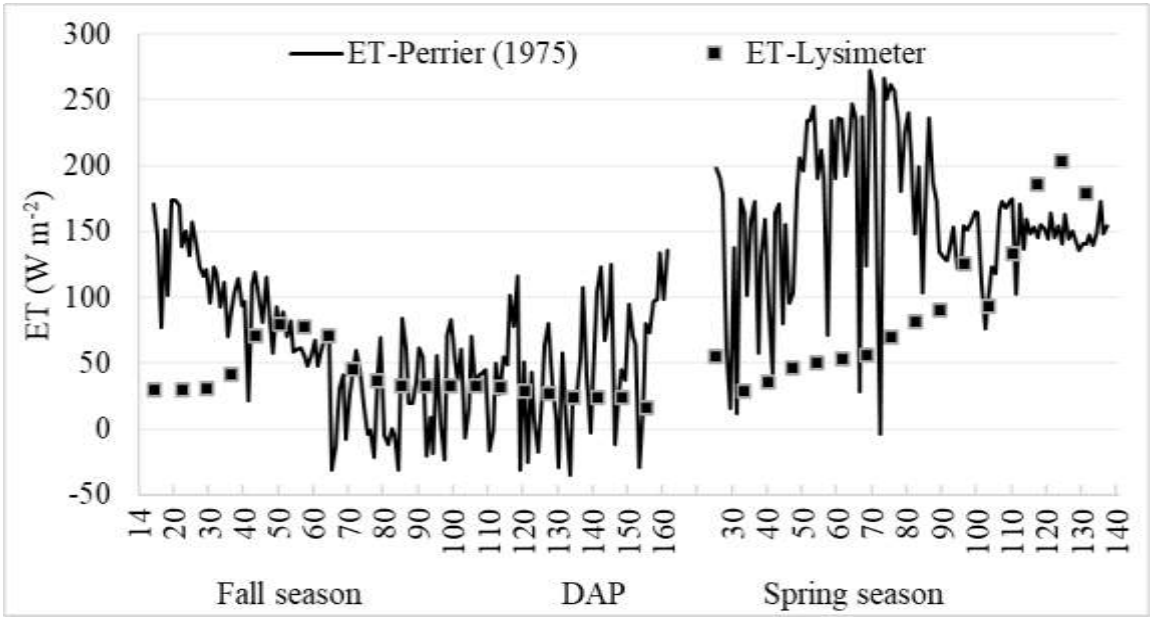


Figure 6. Comparison of ET values of eggplant using the energy balance method calculated by the Perrier (1975) equation and direct lysimeter measurements. *ET is the evapotranspiration and DAP is the days after planting.*

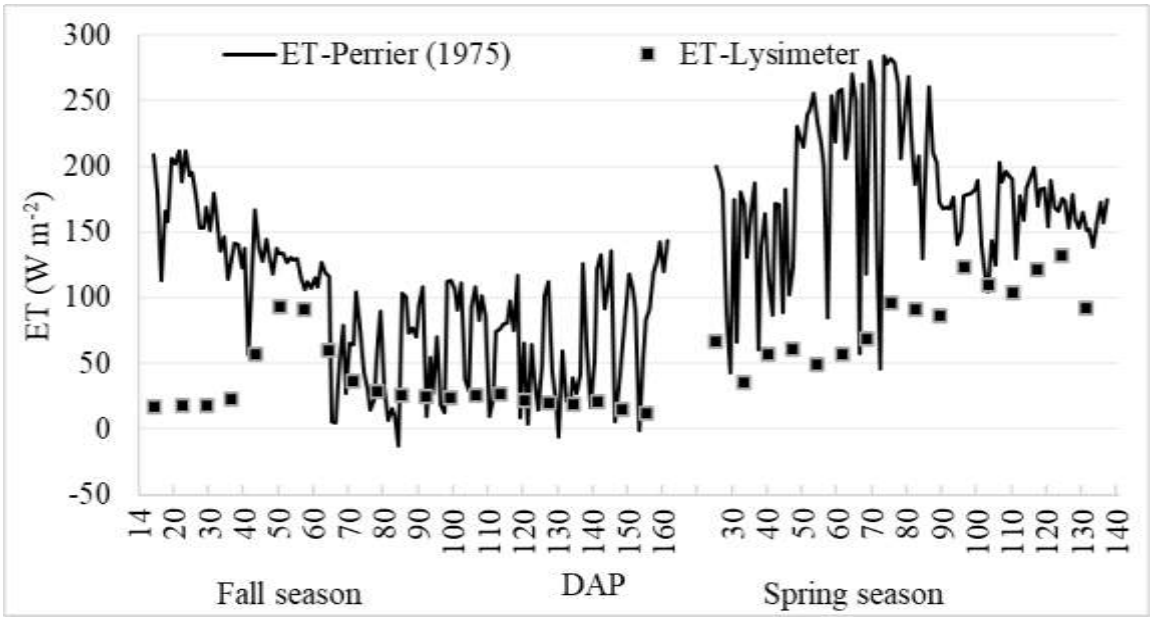


Figure 7. Comparison of ET values of pepper using the energy balance method calculated by the Perrier (1975) equation and direct lysimeter measurements. *ET is the evapotranspiration and DAP is the days after planting.*

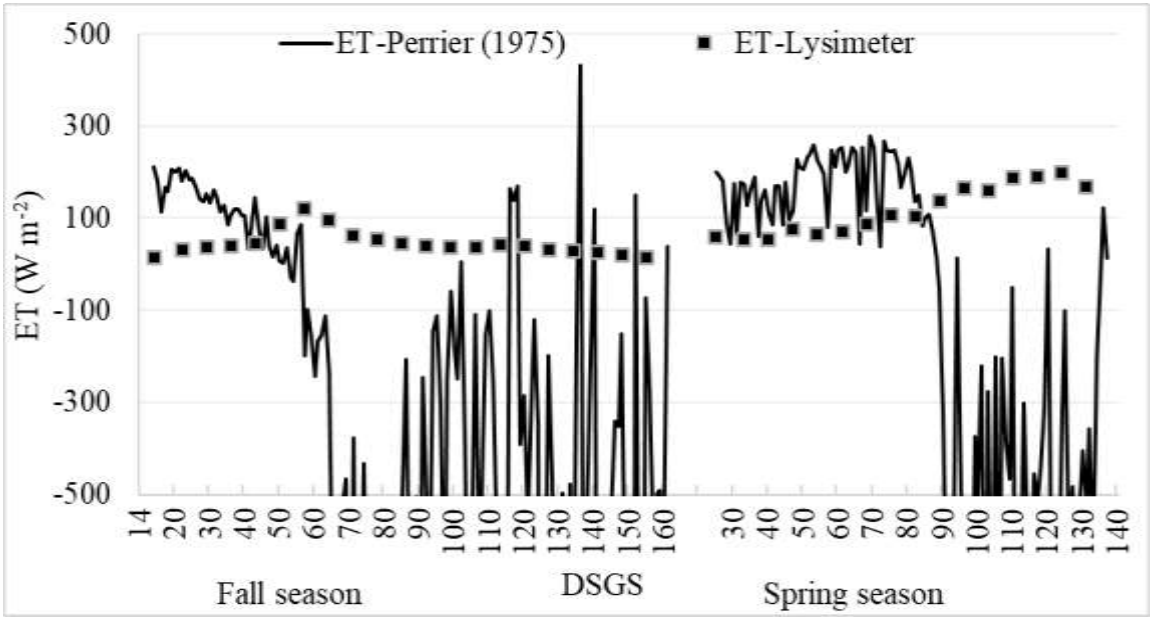


Figure 8. Comparison of ET values of cucumber using the energy balance method calculated by the Perrier (1975) equation and direct lysimeter measurements. *ET is the evapotranspiration and DAP is the days after planting.*

The Brutsaert and Stricker (1979) method (Equation 4) and Perrier (1975) method (Equation 5) were designed to calculate the required aerodynamic resistance (r_a) parameter for the estimation of ET. These two methods were primarily developed to determine the reference evapotranspiration (ET) for comparison with actual plant water consumption under field conditions (Allen et al., 1998). However, some researchers (Gong et al., 2017; Qiu et al., 2013; Yan et al., 2018) have also used these methods directly to estimate the water consumption of certain vegetables under greenhouse conditions.

In the estimation of tomato ET using the Brutsaert and Stricker (1979) method, it was observed that the estimated ET values were significantly higher than the directly measured ET values in both the fall and spring seasons. This method showed the best performance for the tomato plant during the middle and end of the fall season. However, during the spring season, it was not successful in estimating directly measured ET values (Figure 1). Similarly, for eggplant, the Brutsaert and Stricker (1979) method tended to overestimate ET values, especially during the end of the spring season (Figure 2). The estimated ET values showed reasonable agreement with the measured values only towards the end of the spring season. Similar to tomato and eggplant, the Brutsaert and Stricker (1979) method also tended to overestimate the ET values for pepper plants (Figure 3). The estimated ET values were found to be approximately five times higher than the directly measured ET values. In contrast, the Brutsaert and Stricker (1979) method performed better for the cucumber plant compared to other crops (Figure 4). Particularly during the middle of the autumn season and towards the end of the spring season, the method yielded results close to the actual ET values. However, when comparing the estimated ET values with the directly measured ET values throughout the growing season, it is evident that the method was not sufficiently accurate.

In this study, the r_a values for tomato and cucumber crops were calculated using the methods proposed by Brutsaert and Stricker (1979) and Perrier (1975), and the resulting ET values ranged from -13555 (W m^{-2}) to 148121 (W m^{-2}). To better analyze the obtained results, the ET values were standardized between -500 and 500 on the y-axis in Figures 5 and 8. The use of the Perrier (1975) method in the energy balance equation to estimate ET for tomatoes was shown in Figure 5. The relationship between estimated ET values and measured ET values deteriorated in both growing seasons, especially towards the end of each season when ET values became negative. For eggplant, the Perrier (1975) method tended to overestimate ET values compared to measured values (Figure 6). In particular, at the midpoint of the fall season, negative ET values were obtained, and at the beginning of the spring season, higher estimated ET values were obtained than the measured ET values. In contrast, for pepper, this method did not yield negative ET values (Figure 7). However, it tended to significantly overestimate the ET values in both growing seasons, showing approximately five times higher values compared to the measured ET values. On the other hand, for cucumber, the method yielded relatively better results, particularly towards the midpoint of the fall season and the end of the spring season (Figure 8). However, throughout the growing season, the method still did not provide satisfactory estimates compared to the directly measured ET values for all crops.

The methods proposed by Brutsaert and Stricker (1979) and Perrier (1975) determine the aerodynamic resistance (r_a) based on a logarithmic wind speed profile that describes the turbulent transfer of water vapor between the plant canopy surface and the atmosphere (Brutsaert and Stricker, 1979; Yan et al., 2018). However, the wind speed decreases exponentially as it enters the plant canopy (Alves et al. 1998). Moreover, in naturally ventilated greenhouses, wind speed is generally low under natural ventilation. Fernández et al. (2010) reported that the daily measured wind speed values in the greenhouse mostly ranged from 0.01 to 0.2 m s-1. Hence, some researchers (Qiu et al. 2013; Gong et al. 2017; Yan et al. 2018) suggested that when the wind speed is close to zero, the aerodynamic resistance could be infinite, making these equations potentially unsuitable for greenhouse conditions. Fernández et al. (2010) reported oscillation of r_a values between 2.080 and 20.800 s m^{-1} for grass under greenhouse conditions. Therefore, using r_a values calculated with the Brutsaert and Stricker (1979) and Perrier (1975) equations in the ET estimation equation may lead to erroneous results in greenhouse conditions. The findings from this study support this notion. It was determined that the Brutsaert and Stricker (1979) and Perrier (1975) methods were not

suitable for accurately predicting ET values for tomato, eggplant, pepper, and cucumber crops in Mediterranean-type plastic greenhouses during both growing seasons. Therefore, the use of these methods to calculate r_a for ET estimations under similar greenhouse conditions is not recommended. However, some researchers (Gong et al. 2017) mentioned that in greenhouses with ventilation systems, wind speed can be higher than that in naturally ventilated greenhouses, suggesting that the methods could potentially be used with modifications in such greenhouses.

CONCLUSION

In this study, evapotranspiration (ET) values obtained from lysimeters were compared with the ET values obtained through the energy balance method. The aerodynamic resistance (r_a) in the energy balance equation was determined using the Brutsaert and Stricker (1979) and Perrier (1975) methods specifically developed for field conditions. The results of this study indicated that the Brutsaert and Stricker (1979) and Perrier (1975) methods are not suitable for predicting the ET of tomato, eggplant, pepper, and cucumber plants under greenhouse conditions. In particular, the calculated ra values in the energy balance equation led to erroneous results for ET estimation because of the very low wind speed inside the naturally ventilated greenhouses. However, in greenhouses equipped with ventilation systems, where wind speeds are higher than those in naturally ventilated greenhouses, the methods could potentially be improved, and their applicability should be investigated further.

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DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing fnancial interests or personal relationships that could have appeared to infuence the work reported in this paper.

REFERENCES

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration: Guidelines for computing crop water requirements, FAO Irrigation and Drainage Paper 56. FAO, Roma.

Alves, I., Perrier, A., S., P., 1998. Aerodynamıc and surface resıstances of complete cover crops: how good ıs the “BIG LEAF”? Trans. ASAE 41, 345–351.

Bailey, B.J., Montero, J.I., Biel, C., Wilkinson, D.J., Anton, A., Jolliet, O., 1993. Transpiration of Ficus benjamina: comparison of measurements with predictions of the Penman-Monteith model and a simplified version. Agric. For. Meteorol. 65, 229–243.

Brutsaert, W., Stricker, H., 1979. An advection-aridity approach to estimate actual regional evapotranspiration. Water Resour. Res. 15, 443–450. https://doi.org/10.1029/WR015i002p00443

Fernández, M.D., Bonachela, S., Orgaz, F., Thompson, R., López, J.C., Granados, M.R.,

Gallardo, M., Fereres, E., 2010. Measurement and estimation of plastic greenhouse reference evapotranspiration in a Mediterranean climate. Irrig. Sci. 28, 497–509. https://doi.org/10.1007/s00271-010-0210-z

Gong, X., Liu, H., Sun, J., Gao, Y., Zhang, X., Jha, S.K., Zhang, H., Ma, X., Wang, W., 2017. A proposed surface resistance model for the Penman-Monteith formula to estimate evapotranspiration in a solar greenhouse. J. Arid Land 9, 530–546. https://doi.org/10.1007/s40333-017-0020-8

Jolliet, O., Bailey, B.J., 1992. The effect of climate on tomato transpiration in greenhouses: measurements and models comparison. Agric. For. Meteorol. 58, 43–62. https://doi.org/10.1016/0168-1923(92)90110-P

Kjelgaard, J.F., Stockle, C.O., 2001. Evaluating Surface Resistance for Estimating Corn and Potato Evapotranspiration with The Penman–Monteith Model. Trans. ASAE 44, 797–805.

López, A., Molina-Aiz, F.D., Valera, D.L., Peña, A., 2012. Determining the emissivity of the leaves of nine horticultural crops by means of infrared thermography. Sci. Hortic. (Amsterdam). 137, 49–58. https://doi.org/10.1016/j.scienta.2012.01.022

Monteith, J., Unsworth, M., 2013. Principles of Environmental Physics: Plants, Animals, and the Atmosphere: Fourth Edition, Principles of Environmental Physics: Plants, Animals, and the Atmosphere: Fourth Edition. https://doi.org/10.1016/C2010-0-66393-0

Monteith, J.L., 1965. Evaporation and Environment. Symp. Soc. Exp. Biol. 19, 205–234. https://doi.org/10.1613/jair.301

Orgaz, F., Fernández, M.D., Bonachela, S., Gallardo, M., Fereres, E., 2005. Evapotranspiration of horticultural crops in an unheated plastic greenhouse. Agric. Water Manag. 72, 81–96.

Perrier, A., 1975. Etude de l'evapotranspiration dans les conditions naturelles. I- Evaporation et bilan d'energie des surface naturelles. Ann. Agron. 26, 1–18.

Qiu, R., Kang, S., Du, T., Tong, L., Hao, X., Chen, R., Chen, J., Li, F., 2013. Effect of convection on the Penman-Monteith model estimates of transpiration of hot pepper grown in solar greenhouse. Sci. Hortic. (Amsterdam). 160, 163–171. https://doi.org/10.1016/j.scienta.2013.05.043

Rana, G., Katerji, N., 2000. Measurement and estimation of actual evapotranspiration in the field under Mediterranean climate: A review. Eur. J. Agron. 13, 125–153. https://doi.org/10.1016/S1161-0301(00)00070-8

Wang, S., Yernaux, M., Deltour, J., 1999. A Networked Two-Dimensional Sonic Anemometer System for the Measurement of Air Velocity in Greenhouses. J. Agric. Eng. Res. 73, 189–197. https://doi.org/http://dx.doi.org/10.1006/jaer.1998.0403

Yan, H., Zhang, C., Coenders Gerrits, M., Acquah, S.J., Zhang, H., Wu, H., Zhao, B., Huang, S., Fu, H., 2018. Parametrization of aerodynamic and canopy resistances for modeling evapotranspiration of greenhouse cucumber. Agric. For. Meteorol. 262, 370–378.