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## STUDY OF MICROCLIMATE AND SAPLING CITRUS PLANT TRANSPIRATION IN TUNNEL GREENHOUSE UNDER MEDITERRANEAN CONDITIONS

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In Mediterranean basin, citrus culture is expanding rapidly with a growing demand for high-quality saplings. Protected cultivation with fine microclimate conditions control is the best process of citrus saplings growing with the required quality. In this context, the developed microclimate of a tunnel citrus saplings greenhouse and its effects on plant activity parameters, such as leaf temperature and transpiration, were investigated. The findings show that the temperatures of air and plant leaves inside the greenhouse are highly variable between 6 °C and 33 °C and from 8 °C to 30 °C, respectively. Results also show that greenhouse air humidity is very high – more than 80%. The analysis of plant transpiration based on greenhouse microclimate conditions and leaf temperature reveals that (i) plant transpiration varies throughout the day (between 1.9 and 65.7 mg m<sup>-2</sup>·s<sup>-1</sup>); (ii) leaf temperature simulation can be used as an indirect indicator of plant water stress; and (iii) the simulated temperature difference between the leaves and the internal air of the greenhouse can be used to define the minimum threshold air temperature for proper plant development under the greenhouse conditions.

**Keywords:** greenhouse; climate; heat balance; citrus saplings; transpiration

Greenhouse technical production is one of the most frequent solutions used by farmers to increase the production-per-land-unit and to limit the external negative effects on plant comfort (Akpenpuun and Mijinyawa, 2018). Citrus fruit is one of the major crops beneficial for human health due to their nutritional richness (vitamins and minerals). Farmers have given a great importance to citrus fruits production which has experienced a rise in recent years. According to USDA (2020), global orange production for 2018/19 was around 53.844 million tons in the Mediterranean area. Morocco cultivates citrus fruits on 129.000 ha of land, with an average production of 1.765 million tons (USDA, 2018). Improving citrus productivity depends mainly on the quality of saplings used to cultivate fruit trees. The increasing demand for high agricultural quality products leads to placing emphasis on producing saplings in greenhouses, which allows for better climate control during their growing period, showing the importance of studying accurately the microclimate conditions under which these plants are grown.

According to academic literature, most studies on citrus fruits are conducted on fully mature trees in open field. A rare study focused on citrus greenhouse production was carried out by Yang et al. (2003). This study showed that evapotranspiration (ET) has significant seasonal variations reaching its maximum value between 9 am and 12 am for winter and summer, respectively. On the other hand, Rana, Nader and De Lorenzi (2005) studied the ET of an irrigated citrus (Clementine) orchard under Mediterranean climate.

Er-Raki et al. (2009) estimated citrus orchard ET using eddy covariance measurements, with results 20% lower compared to single and dual crop coefficient approaches from FAO-56. Regarding canopy conductance (g) and transpiration (T), Villalobos, Testi and Moreno-Perez (2009) and Villalobos et al. (2013) developed a conductance model based on intercepted radiation and CO<sub>2</sub> assimilation for different fruit trees (including citrus) in Mediterranean areas. Meanwhile, Rana, Nader and De Lorenzi (2005) used an empirical model relating bulk canopy resistance to aerodynamic resistance based on Katerji formula (Katerji et al., 1983). In South Africa, on a 9-year-old citrus crop (Valencia Midnight), Vahrmeijer and Taylor (2019) found that transpiration (T) follows diurnal and seasonal trends, with a clear correlation between crop transpiration and climatic parameters such as temperature, solar radiation, vapour pressure deficit (VPD) and *ET<sub>c</sub>*.

Admittedly, there are several methods for measuring crop transpiration, but they are all laborious and sometimes expensive. Indirect estimation based on the climatic parameters measurements of the plant environment remain a good alternative for approaching the exact value of the plant transpiration (Boulard et al., 2017).

In this regard, thermography has been widely proposed as a practical approach to circumventing the limitations of porometry in studying stomatal closure in response to stress. These remote sensing approaches have the great advantage of quickly detecting large areas of the vegetation cover with minimal interference with crops. Jones (1999)

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and Jones et al. (2002) tested leaf temperature as an indicator of plant water stress using infrared thermometry for estimation of stomatal conductance.

Vieira and Ferrarezi (2021) developed a method to measure canopy temperature using thermal imaging in one-year-old citrus plants in a greenhouse to identify plants with water stress and verify its potential to be used as a tool to assess citrus water status.

According to Primo-Millo and Agustí (2020), the citrus crop growth is greatly affected by temperature. In subtropical spring, a temperature within the range from 12 °C to 20 °C produces more twigs and short internodes, while during the summer, a temperature between 25 °C and 35 °C produces fewer twigs but with longer internodes. The authors also concluded that root growth depends on the soil temperature to a great extent. Root growth begins slowly for a substrate temperature less than 13 °C and is linear for a substrate temperature range between 18 °C and 30 °C and becomes limited for a substrate temperature above 36 °C. Finally, the citrus plants enter a dormant period at air temperature below 12 °C. The temperature also affects the photosynthesis and stomatal conductance, which reduces significantly above 30 °C with a significant vapour pressure difference (Khairi and Hall, 1976a); around a VPD of 1.8 KPa, the photosynthesis is constant and becomes linear above this value (Khairi and Hall, 1976b).

All the aforementioned studies show that citrus ET has been thoroughly studied, however, no research has been performed in nursery greenhouse conditions on citrus saplings. Therefore, the aim of the current study is to experimentally characterize the real greenhouse microclimate conditions and to investigate its impacts on citrus saplings activities in particular transpiration, as well as the relationship between leaf temperature and the greenhouse microclimate parameters.

## Material and methods

### The studied greenhouse and climatic parameter's measurements

The current study was carried for 12 days in a tunnel plastic greenhouse (Fig. 1) with 64 m in length and 8.6 m in width. This greenhouse is located in the middle region of Morocco (latitude: 33° 53' 36" N; longitude: 5° 32' 50" W; elevation above sea level: 531 m).

The greenhouse roof is covered with 300 µm polyethylene transparent plastic film. A green shade net

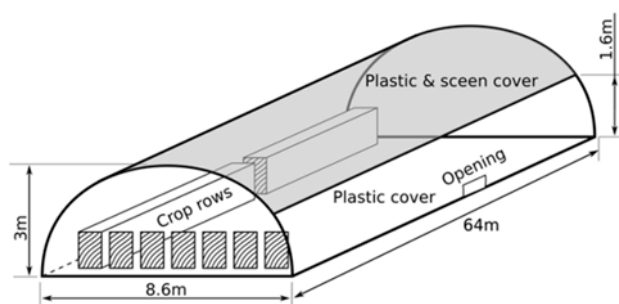


Fig. 1 Schematic view of the studied greenhouse

has also been placed over the plastic cover to reduce solar intensity inside the greenhouse. The inside soil is covered with black plastic mulch. The greenhouse is fully closed, and its ventilation was ensured by the door (2.66 m<sup>2</sup>) in the south-west face.

Citrus saplings are cultivated in seven crop rows with 32 plants·m<sup>-2</sup> of plant density and a height of 0.9 m.

Measurements of air temperature and humidity inside the greenhouse were conducted using SHT35 sensors placed lengthwise in locations A<sub>1</sub>, A<sub>2</sub>, A<sub>3</sub>, A<sub>4</sub>, A<sub>5</sub>, A<sub>7</sub> and A<sub>9</sub> at 30 cm above crops (Fig. 2).

Furthermore, to define the widthwise microclimate profile within the crop, the air temperature and humidity at three places (A<sub>6</sub>, A<sub>7</sub> and A<sub>8</sub>) in the middle of the greenhouse were also recorded. PT100 thermocouple sensors were employed for measuring leaf temperatures at A<sub>7</sub> and A<sub>8</sub> locations.

Greenhouse soil, roof cover plastic and substrate temperature were measured in A<sub>3</sub>, A<sub>6</sub> and A<sub>7</sub> locations, respectively. The net radiation was also acquired inside the greenhouse in A<sub>7</sub> location using ST-1307 solar power meter.

Global radiation, wind speed and direction, air temperature and humidity were continuously monitored outside of the greenhouse using a weather station fixed to a mast.

### Theory

The equation of the energy balance of plants is given as a function of the net radiation  $R_{net}$  and the fluxes of sensible  $Q_{sen}$  and latent  $Q_{lat}$  heat exchanged between the leaves and greenhouse air (Demrati et al., 2001):

$$R_{net} + Q_{lat} + Q_{sen} = 0 \quad (1)$$

where:  $R_{net}$  – net radiative flux (W·m<sup>-2</sup>);  $Q_{lat}$  – latent heat flux (W·m<sup>-2</sup>);  $Q_{sen}$  – sensible heat flux (W·m<sup>-2</sup>)

The latent heat flux is the result of water exchange between leaves and the greenhouse air; therefore, it is equal to the latent heat for the evapotranspiration flux ET (resulting from plant transpiration and soil evaporation), while the sensible heat is expressed as convective flux with respect to leaf temperature  $T_v$  and greenhouse air temperature  $T_{ai}$  (Demrati et al., 2001):

$$R_{net} - L_v \cdot ET - h_s (T_v - T_{ai}) = 0 \quad (2)$$

where:  $L_v$  – specific latent heat (J·kg<sup>-1</sup>);  $ET$  – evapotranspiration flux (kg·m<sup>-2</sup>·s<sup>-1</sup>);  $h_s$  – heat transfer coefficient between leaf surfaces and the air (W·m<sup>-2</sup>·K<sup>-1</sup>);  $T_v$ ,  $T_{ai}$  – crop and greenhouse air temperatures, respectively (°C)

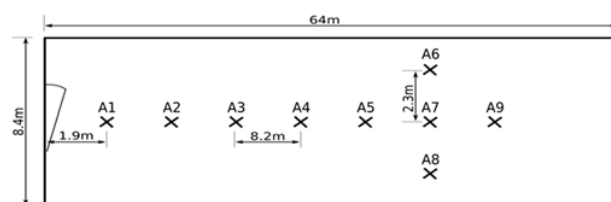


Fig. 2 Schematic view of the inside studied greenhouse measurement locations

$$ET = \frac{R_{net}}{L_v} + \frac{h_s}{L_v} \cdot \Delta T_v \quad (3)$$

where:  $\Delta T_v = T_{ai} - T_{vr}$  – leaf and greenhouse air temperature difference ( $^{\circ}\text{C}$ )

Experimental data (Fig. 6) allowed determination of the relationship between the net radiation  $R_{net}$  and  $\Delta T_v$  (greenhouse and leaf temperature difference), suggesting that  $R_{net}$  is a linear function of  $\Delta T_v$ :

$$R_{net} = C_1 \cdot \Delta T_v + C_2 \quad (4)$$

where:  $C_1, C_2$  – constants coefficients

After regression, slope and intercept  $C_1$  and  $C_2$  can define experimentally.

Therefore,  $ET$  can be written as follows:

$$ET = \frac{C_1 + h_s}{L_v} \cdot \Delta T_v + \frac{C_2}{L_v} \quad (5)$$

Finally, it is observed that the  $ET$  is a linear function of  $\Delta T_v$ , and it can be expressed as follows:

$$ET = A_1 \cdot \Delta T_v + A_2 \quad (6)$$

where:  $A_1 = \frac{C_1 + h_s}{L_v}$ ;  $A_2 = \frac{C_2}{L_v}$

On the other hand, plant transpiration can be deduced from Penman-Monteith formula (Penman, 1948) (Eq. 7) based on experimental data and calculated parameters:

$$L_v ET = \frac{\Delta R_{net} + \rho_a C_p \frac{D_a}{r_a}}{\Delta + \gamma \left( 1 + \frac{r_s}{r_a} \right)} \quad (7)$$

where:  $\Delta$  – slope of saturation vapour pressure curve ( $\text{kPa} \cdot ^{\circ}\text{C}^{-1}$ );  $\rho_a$  – air density ( $\text{kg} \cdot \text{m}^{-3}$ );  $C_p$  – specific heat capacity ( $\text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$ );  $r_a, r_s$  – leaf aerodynamic and stomatal resistance, respectively ( $\text{s} \cdot \text{m}^{-1}$ );  $\gamma$  – psychrometric constant, deductible from Eq. 8

$$\gamma = \frac{C_p p}{\varepsilon} \quad (8)$$

where:  $p$  – atmospheric pressure (kPa);  $\varepsilon$  – ratio molecular weight of water vapour/dry air ( $\varepsilon = 0.622$ )

The vapour pressure deficit of air  $D_a$  is then calculated as follows:

$$D_a = e_s - e_a \quad (9)$$

The saturation vapour pressure  $e_s$  can be calculated based on the equations given by Tetens (1930):

$$e_s = 0.6108 \exp\left(\frac{17.27 T_a}{T_a + 237.3}\right) \quad (10)$$

$$e_a = \frac{RH e_s}{100} \quad (11)$$

where:  $RH$  – relative humidity (%)

The leaf aerodynamic resistance  $r_a$  was given by Campbell (1986):

$$r_a = 840 \left| \frac{l}{T_v - T_a} \right|^{0.25} \quad (12)$$

where:  $l$  – characteristic leaf length (m)

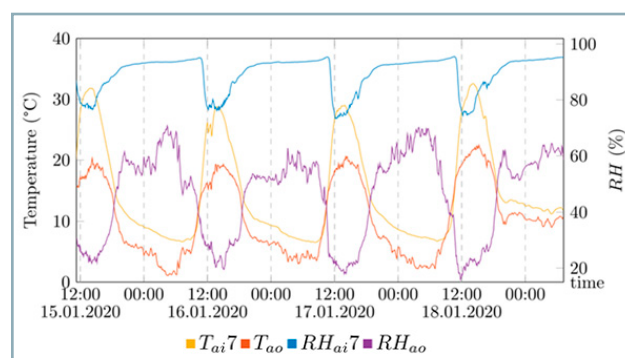
The slope of saturation vapour pressure curve  $\Delta$  was given by Allen et al. (1998):

$$\Delta = \frac{4098 \left( 0.6108 \exp\left(\frac{17.27 T_{ai}}{T + 237.3}\right) \right)}{(237.3 + T_{ai})^2} \quad (13)$$

## Results and discussion

### Detailed interior greenhouse microclimate analysis

Fig. 3 shows that air temperature and relative humidity vary periodically according to the day cycle. The air temperature development has the same profile as external solar global radiation, which explains its significance in determining greenhouse microclimate.



**Fig. 3** Interior and exterior greenhouse air temperature and relative humidity profile

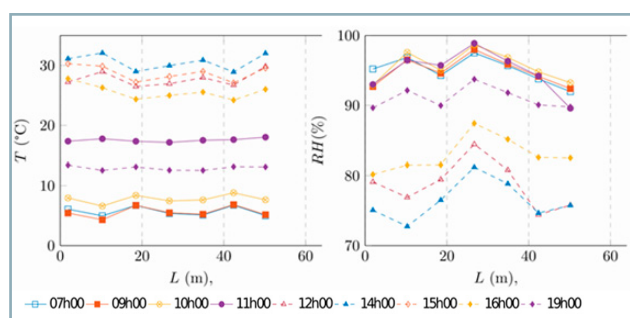
For sunny days, there was observed an important increase in the interior air temperature and humidity during the daytime period compared to exterior ones, the maximum difference values of these two parameters were reached at midday – 14  $^{\circ}\text{C}$  in temperature and 55% in humidity. Differences above 8  $^{\circ}\text{C}$  in temperature and 55% in humidity persisted for 2 h 30 min and 8 h 20 min, respectively. These results confirm the significance of the greenhouse effect caused by solar radiation despite the use of the green shade net above the plastic cover. Contrarily, in a tomato canary greenhouse, diurnal interior relative humidity was much lower than the exterior one in the same period, which might have been caused by greenhouse type and plants' activity on greenhouse microclimate development (Majdoubi et al., 2007).

During the night-time period, there was also a large difference between interior and exterior air climate conditions. The experimental data show that interior air humidity reached the saturation value of 98% and maintained a value above 92% for 12 hours while the exterior humidity did not exceed 70% (for all the night). Considering the air temperature, there

was a slight difference between the two areas compared to the daytime; the maximum difference value reached 6 °C with a value above 4 °C (for 6 h) (Fig. 4). This difference was due to the release of thermal energy stored in the soil covered by a black plastic mulch and in the substrate during the daytime.

Furthermore, the temperature air difference became lower at the end of night, which indicates the effect of plastic cover on the thermal inversion during night-time, especially before sunrise time.

In terms of spatial distribution of climate in the greenhouse, Fig. 4 confirms the heterogeneity of temperature and humidity fields along the greenhouse.



**Fig. 4** Greenhouse air temperature and relative humidity distribution along the greenhouse length

In middle of the day, air temperature and relative humidity were more heterogeneous, particularly between 14 h and 15 h. The air temperature near the end of the sides was higher than along the greenhouse length and width (Fig. 4). This effect was greater while going widthwise toward the greenhouse ends.

Considering the relative humidity, according to the width, the sides end areas were more humid than the middle, conversely, along the greenhouse length; the middle areas were more humid than the sides end areas (Fig. 4).

Results also show that the air temperature within the crop row at the greenhouse centre was lower than that above canopy, the difference value reached 3.7 °C. This difference became lower near the sides wall area, especially in the east part. During the diurnal period, the average canopy air temperature reached 23 °C. This value is suitable for citrus growth which needs an optimal temperature range from 12 °C to 30 °C. These optimal conditions persisted for 9 h. However, the plant activity became dormant for 15 h characterized by a low air temperature around 6.7 °C, especially during the nocturnal period.

Highlights from this interior greenhouse microclimate analysis: (i) the significant effect of the shade net on greenhouse solar radiation reduction; (ii) the excess of air humidity in the lower greenhouse parts, which is a problem that can be solved by the natural ventilation of the greenhouse; (iii) the need to install a thermal screen inside the greenhouse that will be deployed at night to reduce heat losses.

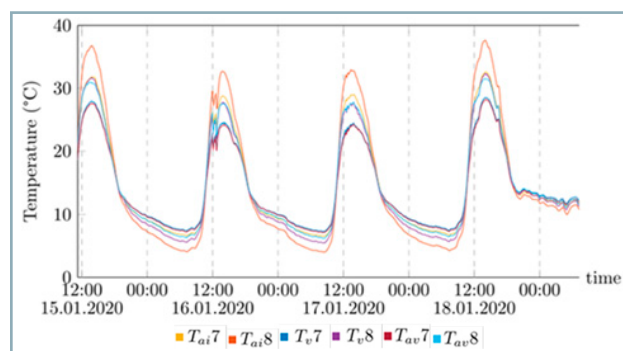
### Plant leaf temperature and transpiration flux

#### Leaf temperature

During daytime, this study (Fig. 5) shows that the leaf temperature was significantly lower than that of the greenhouse air measured above the crop row. However, this

difference becomes much weaker overnight. Moreover, the crop leaf temperature was very close to the air temperature within the crop rows. The same result was found by Majdoubi (2007) and Errais et al. (2020) for tomato canary and venlo greenhouses, respectively.

Furthermore, results reveal that the leaf temperature was not uniform throughout the greenhouse and showed the same trend as the greenhouse air temperature measured above the canopy. In fact, this temperature was higher towards the sidewall than that in the greenhouse centre during the diurnal period, and the opposite was true during the nocturnal period. This result is due to the greenhouse design which makes the vegetation height level closer to the greenhouse roof in areas near the walls.



**Fig. 5** Greenhouse air and leaf temperature profiles at different locations

Fig. 6a shows a linear correlation between the net radiation above canopy and leaf and greenhouse air temperature differences  $\Delta T_v = T_{ai} - T_v$ , with a high linear correlation coefficient ( $R^2 = 90\%$ ) (14):

$$R_{net} = 38.76 \cdot \Delta T_v + 32.95 \quad (14)$$

Fig. 6b shows strong correlation between the vapor pressure deficit (VPD) values and leaf temperature difference to the greenhouse air. The relationship (Eq. 15) shows a polynomial correlation with a determination coefficient ( $R^2 = 96.76\%$ ).

$$\Delta T_v = -5.48 \cdot VPD^2 + 11.26 \cdot VPD - 1.29 \quad (15)$$

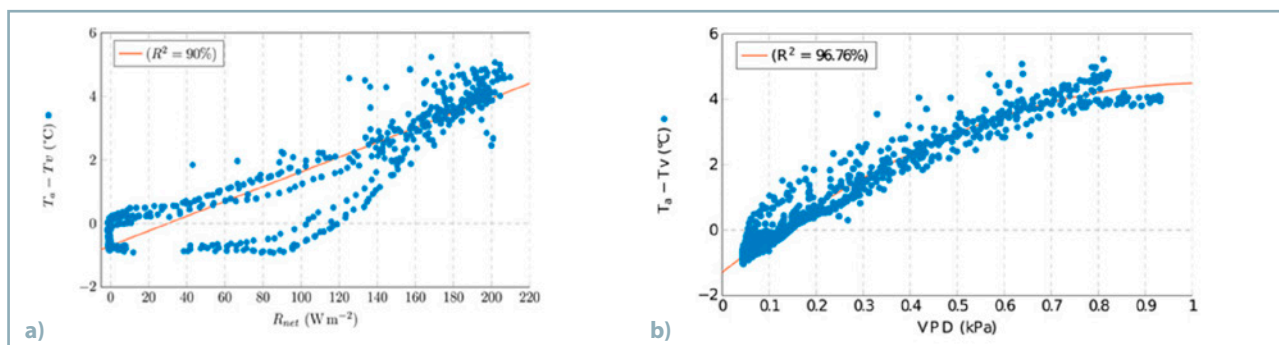
A multiple linear regression of these results concerning the behaviour of leaves and greenhouse air temperature values compared to the climate conditions as  $T_{ai}$ ,  $RH$  and  $R_{net}$ , led to search for a model of this difference according to previous three combined parameters.

$$\Delta T_v = T_{ai} - T_v = 0.0852 \cdot T_{ai} + 0.0032 \cdot R_{net} - 0.1334 \cdot RH + 11.0895 \quad (16)$$

The correlational analysis results show significant relationship between  $\Delta T_v$  and the three parameters  $T_{ai}$ ,  $RH$ ,  $R_{net}$  with an adjusted  $R^2$  value of 96.91%. Therefore, all three parameters were significant predictors.

#### Transpiration flux

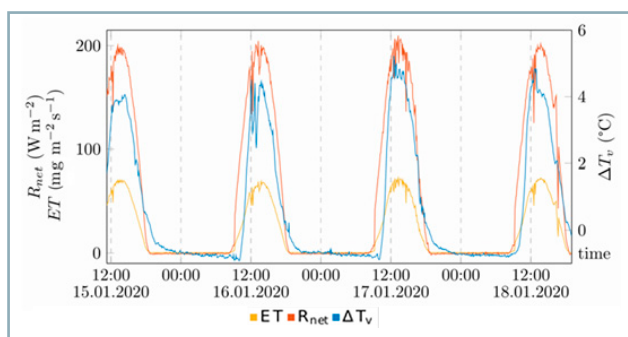
Fig. 7 illustrates the evolution of plant transpiration, the greenhouse net radiation and the temperature difference



**Fig. 6** Greenhouse air and leaf temperature difference ( $\Delta T_v$ ) versus (a) greenhouse net radiation ( $R_{net}$ ) and (b)  $VPD$

between the air and leaf over time. Clearly, results show that the previously cited parameters have the same profile evolution. Moreover, leaf transpiration follows the net radiation and temperature difference evolution. The transpiration rate is high during daytime period (for 9 h), especially after 11 am, and its maximum value reaches  $72 \text{ mg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ . However, it does not exceed 0.6 in  $\text{mg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  during all the night-time (15 h) (Table 1).

Results of transpiration flux as a function of the temperature difference between the air and the leaves at various times of day show that the citrus transpiration varies linearly with temperature difference between 8 am and 6 pm and nonlinearly between 6 pm and 8 am, which allows the determination of coefficients  $A_1$  and  $A_2$  from Eq. 6 for the three observed periods (Table 1).



**Fig. 7** Leaf transpiration, greenhouse net radiation flux and temperature difference profiles

The climate conditions inside the studied greenhouse are characterized by a low irradiative intensity (average value  $72 \text{ W}\cdot\text{m}^{-2}$ ), a weak ventilation rate, a weak  $VPD$  value and a low air temperature (average value of  $23.2 \text{ }^\circ\text{C}$  during daytime and  $8 \text{ }^\circ\text{C}$  during night-time); however, relative humidity is always higher than 84% in daytime and 93% in night-time, neither of which is favourable to citrus plant sapling transpiration.

These conditions explain crop pathogen and plant fungal disease (De Vallavieille et al., 2018; Patt et al., 2015; Aguilera-Cogley et al., 2017; Li et al., 2018; Fatnassi et al., 2021) observed by farmers. Additionally, the water condensation easily covers plants, creating the ideal conditions for the spores to fungal germinate quickly. It can also weaken culture and make it more susceptible to changes in climate parameters, which explain the citrus sapling production delay and damage declared by farmers.

**Conclusion**

The research presented sought to characterize the microclimate and activity of citrus plants in a tunnel greenhouse during the winter season. The study revealed the significance effect of using a shade net to reduce solar radiation inside the greenhouse during the day, as well as the effect of reducing ventilation on the increase of air humidity inside the greenhouse. This excess humidity may increase the risk of plant disease development. The findings also showed that the substrate temperature was lower than the greenhouse temperature during the day and was always

**Table 1** Greenhouse climate parameters and plant transpiration flux

Period	$\Delta T_v = T_v - T_{ai}$ ( $^\circ\text{C}$ ) ( $\pm 0.2$ )	Relative humidity RH (%) ( $\pm 1.5$ )	Net radiation $R_{net}$ ( $\text{W}\cdot\text{m}^{-2}$ ) ( $\pm 10$ )	Transpiration $ET$ (Penman-Monteith Eq. 7) ( $\text{mg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ ) ( $\pm 3$ )	Coefficients $A_1$ and $A_2$ of Eq. 6
Daytime	8 h to 11 h	min 94.1 max 95.5 avg. 94.8	min 7 max 137 avg. 78	min 1.9 max 38.3 avg. 19.4	$A_1 = 14.56$ $A_2 = 25.32$
	11 h to 15 h	min 73.3 max 94.2 avg. 78.3	min 125 max 210 avg. 181	min 38.3 max 72.8 avg. 62.2	$A_1 = 7.52$ $A_2 = 33.80$
	15 h to 18 h	min 77.4 max 88.7 avg. 84.1	min 13 max 193 avg. 110	min 4.7 max 65.7 avg. 36.6	$A_1 = 16.00$ $A_2 = 4.63$
Night-time	18 h to 8 h	min 88.0 max 94.6 avg. 92.8	$\ll 12$	$\ll 4.3$	$ET$ does not correlate to $\Delta T_v$

within the plant's optimal range. However, at the end of the day and during the night, the substrate temperature rose above the greenhouse air temperature and fell slightly below the minimum temperature value to ensure proper root development.

Plant transpiration analysis according to the greenhouse microclimate conditions and leaf temperature showed that the plant transpiration varied along the day and its values were low compared to the literature.

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