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INFLUENCE OF EVAPORATIVE COOLING SYSTEM ON MICROCLIMATIC CONDITIONS OF A NURSERY SHADED GREENHOUSE

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ABSTRACT

In this research trail an attempt has been made to analyse the thermal gradient being developed along the direction of the airflow of evaporative cooling system based on cooling pads and extracting fan. A small shaded gable-even-span greenhouse was used as a nursery for germinating seeds of sweet colour pepper and growing the seedlings until transplanting. The experimental work was carried out under the climatic conditions of eastern area of coastal delta, Egypt (latitude angle of 31º 02' 41" N, longitude angle of 31º 21' 55" E, and mean altitude above sea level of 16 m), during summer season of 2013.High temperature gradients of this type can markedly affect seedlings growth, and growers often combine evaporative cooling system with shading. To predict the temperature gradients along a small greenhouse, a simple climatic model was proposed which incorporates the effect of ventilation rate, roof shading, and plant evapotranspiration rate. In order to validate the proposed model, different measurements were accomplished in a small shaded greenhouse equipped with cooling pads and extracting fan.

Experimental data revealed that the evaporative cooling system was able and adequate to keep and maintain the greenhouse indoor air temperature at desired level. The model was validated by fitting measured air temperatures after cooling pads directly, at the middle and before the extracting fan of the greenhouse. It was used to study: the influence of different cooling air temperatures combined with shading on the air temperature profiles along the greenhouse length, and the influence of outside air temperature and relative humidity on the effectiveness of the evaporative cooling system. The proposed model is sufficiently accurate to improve the design and the management of the evaporative cooling system. Due to the optimal level of microclimatic conditions of the shaded greenhouse, the sweet colour pepper seeds being germinated after 8 days from the sawing operation, and the seedlings reached to the transplanting stage after 6 weeks.

INTRODUCTION

Reducing indoor air temperatures is one of the main problems facing greenhouse management in warm and hot climates. One of the most efficient ways to reduce the difference between indoor and outdoor air temperature is the ventilation system. Natural or passive ventilation system uses very little external energy as opposed to active or forced ventilation, but it increases the complexity of greenhouse structure and makes climate control more difficult. Various technical equipments can efficiently contribute to maintain greenhouse indoor air temperature and relative humidity at acceptable levels during hot periods. However, adequate models may be necessary to estimate the cooling loads and adequately manage such climate control equipment.

Roof shading and evaporative cooling system based on cooling pads and extracting fans are the most common techniques used to prevent plant stress and produce crops of marketable quality. Shading black screens mounted externally or internally, may be used to reduce solar radiation intensity inside the greenhouse but the effective temperature reduction is not really proportional to the shading rate (Kittas et al., 2003). Willits and Peet (1993) showed that externally mounted black polyethylene films were less than 50% effective in reducing energy and temperature gains compared to their commercially given values, while white shading cloths were only slightly more effective.

Ventilation reduces greenhouse overheating, but it may even enhance the risk of water stress because it often increases plant transpiration. Kittas *et al.* (2001a) reported that high rates of ventilation were not, a priori, the best solution for alleviating crop stress in greenhouses during summer conditions is evaporative cooling system that substantially improves the greenhouse climatic conditions. It can be done by spraying water droplets in a naturally ventilated building (by low-or high pressure fog systems), or by forcing ambient air through wet cooling pads. Both produce a temperature drop with an absolute humidity rise in the greenhouse, which contributes to decrease the vapour pressure deficit and moderate the transpiration demand (Katsoulas et al., 2001). The efficiency of fog systems is often limited by insufficient natural air convection, in the absence of wind, and by the risk of wetting the plants when water droplets evaporation is not complete Kittas *et al.* (2003).

The main disadvantage of evaporative cooling systems base on cooling pads and extracting fans is the creation of large temperature gradients inside the greenhouse, from cooling pads on one side to extracting fans on the opposite side. Due to the significant length of greenhouse (60 m), large temperature gradients (up to 8ºC) were observed from cooling pads to extracting fans (Kittas et al., 2003). The amplitude of such gradients is affected by many factors, and only a numerical model can predict its value. Various experimental works on evaporative cooling systems applied to horticulture, mainly for systems, were already published, and, among others, those by Montero *et al.* (1990) and Camargo *et al.* (2003). Most of these works analyse the thermodynamics efficiency of the system and its climatic effects. Willits (2000) proposed a model to predict air and crop temperatures as a function of ventilation rate and external temperature.

Recently, Kittas *et al.* (2001b) presented sensible and latent heat profiles observed along a large greenhouse, and, in order to explain their results, they proposed a model, which simulates the air temperature distribution inside the enclosure. However, this model was neither calibrated nor validated against experimental data. Camargo *et al.* (2005) presented the basic principles of the evaporative cooling in order to determine the effectiveness of saturation based on the mathematical development of the equations of thermal exchanges. Their experimental results were used to determine the convective heat transfer coefficient and compared with the mathematical model.

Therefore, the aim of the present experimental trail was to propose a simple model including crop effect, and validate it against measurements data in a small greenhouse. The model predicts indoor air temperature profiles and can be used to improve large greenhouse design.

MATERIALS AND METHODS

Materials

Greenhouse position and equipment

The experimental work was carried out from July to August 2013 in gable-even-span single greenhouses, E-W orientated, and located at the University of Mansoura (eastern area of coastal delta, Egypt, latitude angle of 31º 02' 41" N, longitude angle of 31º 21' 55" E, and mean altitude above sea level of 16 m). The geometric characteristics of greenhouse are as follows: eaves height 3.27 m, height of each side wall 2 m, rafter angle 27^o, width 4 m, length 8 m, floor surface area 32 m^2, and volume 87.7 m^3 as shown in **Fig. (1)**. The greenhouse was covered using glazing material of 800μm thick corrugated fiberglass reinforced plastic (FRP). The greenhouse facility used in this research work was covered with the ratio of cover surface area to the total greenhouse surface area of 2.685. The gable roof and southern wall was covered by 50% black screen to reduce the intensity of solar radiation.

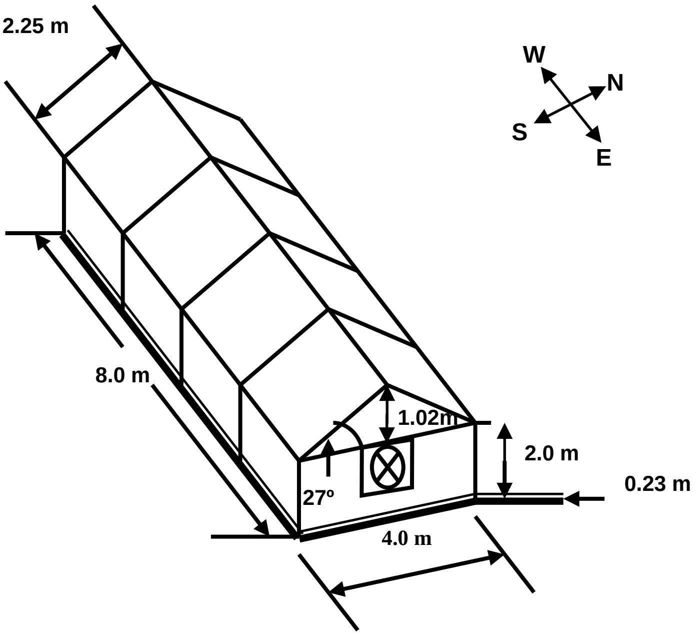

Fig. (1): Schematic diagram of gable-even-span greenhouse.

Ventilation and cooling systems

Ambient air was forced through 1.80 m^2 face area of 0.10 m thick cooling pads situated on the middle of the western wall (side toward the prevailing winds). These corrugated cellulose pads permit 75 m/min air speed. A polyvinyl chloride (PVC) pipe (12.5 mm diameter) was suspended immediately above the pads. Holes were drilled in a line about 5 cm apart along the bottom side, and the end of this pipe was capped. A baffle was placed above the water pipe to prevent any leaking of water from the system. A sump (gutter) was mounted under the pads to collect the water and return it into the water tank from which it can be recycled to the pads by the pump. After crossing the pads, air travels an 8 m distance before being extracted by one fan located on the opposite side wall (eastern wall). Extracting fan generated an airflow rate of about 8100 m^3/h under 2.5 mm static pressure. The evaporative cooling system was continuously operated when the outdoor air temperature of the greenhouse was higher than 20°C. The air temperature inside the greenhouses, at a height of about 1.8 m above floor level (monitor), was controlled by an on-off controller (differential thermostat) to initiate ventilating at 28ºC and interrupt it at 24°C.

Cultivation system

The nursery (small shaded greenhouse) was disinfected on 20th of June 2013. Soil mix-media for germinating sweet coloured pepper consisted of one bag of peat-moss (60 kg) and four bags of vermiculite (each bag 15 kg weigh) were used. The peat-moss bag (volume of 0.3 m^3 and 60 kg weigh) was manipulated and enriched by adding little amount of chemicals (75 g of Rizolex-T 50% as a disinfectant substance, 500 g NPK fertilizer 19-19-19, 150 g of super phosphate, 100 g of potassium sulphate, and 75 g of iron as an enriched materials). Forty eight vegetative trays (84 growth blocks) were used to germinate the seeds of sweet pepper. The tray blocks were full by soil mix- media and 2000 seeds (Imperio, cv. and Tirza, cv., Enza Zaden, Netherlands) were directly planted on 25th of June 2013. After one week the sweet pepper seeds were emerged in the vegetative trays with 96.5% germination ratio and stayed in the nursery until the seedlings reached to four real leaves instance on 17th of August 2013.

Measurements and data acquisition unit

The solar radiation, dry and wet-bulb air temperatures, air relative humidity, and wind speed and its direction outside the greenhouses were measured and recorded using meteorological station (Vantage Pro 2, Davis, USA) which located just above the greenhouse. Another meteorological station (Watch Dog model 550) for internal microclimate variables within the centre of the greenhouse was installed at an altitude of 1.8 m above the ground surface. The internal microclimate variables included global solar radiation above the vegetative trays (2.25 m), dry-bulb air temperature, and air relative humidity. A 12 channel data-logger (Digi-Sense Scanning Thermometer Type) was also used for collecting and recording reading from the different sensors (thermocouples type K) located inside the greenhouse (only five channels were used). Five thermocouples were functioned to measure the interior air temperatures along the centerline of greenhouse at a distance of 0 m (cold air just leaving the cooling pads), 2 m, 4 m, 6 m and 8 m (before extracted out). The measured and recorded data were stored in the memory for output to a printer or in a computer for storage on disk. The time interval for data recording was 5 minutes with data acquisition every one minute for integrated measurements. The calibration of all sensors and the logger was completed successfully at the beginning of the experimental work.

Methods:

Theoretical consideration

There are five parameters affected the temperature distribution along the greenhouse: ventilation rate, plant transpiration and soil evaporation, percentage of shading, water evaporation from the cooling pads, and overall heat transfer coefficient of the cover material. The solution of the energy balance equation combines these parameters and gives access to the temperature distribution along the greenhouse length can be expressed as (Kittas et al., 2003):

$$T_{ai}(x) = T_{ao} + A_1 + [(T_{pad} - T_{ao} - A_1) \exp(-A_2 x)] \qquad (1)$$

Where, T_{ai}, is the indoor air temperature in ºC, x, is the distance at which the air temperature was measured in m, T_{ao}, is the outdoor air temperature in ºC, T_{pad}, is the cooled air just leaving the cooling pads in ºC, and the coefficients A_1 and A_2 are given by:

$$A_1 = \frac{R_i \, A_f \, (1 - \alpha)}{V_a \, \rho \, C_p}, \ {}^{o}C \qquad (2)$$

$$A_2 = \frac{U_o \, P}{V_a \, \rho \, C_p}, \ 1/m \qquad (3)$$

Where, R_i, is the solar radiation flux incident inside the greenhouse in W m^{-2}, A_f, is the floor surface area of the greenhouse in m^2, α, is the ratio of evapotranspiration to solar radiation, V_a, is the ventilation rate in $m^3 \, s^{-1}$, ρ, is the air density in kg m^{-3}, C_p, is the specific heat of saturated air in J $kg^{-1} \, {}^{o}C^{-1}$, U_o, is the overall heat transfer coefficient of the fiberglass cover in W $m^{-2} \, {}^{o}C^{-1}$ and, P, is the perimeter of greenhouse in m. The cooling efficiency (η, %) can be computed using the following equation (ASHRAE, 2005):

$$\eta = \frac{T_{ao} - T_{pad}}{T_{ao} - T_{aow}} \times 100 \qquad (4)$$

Where, T_{aow}, is the wet-bulb temperature of the outdoor air in ºC. Two main parameters are crucial for an accurate prediction of the greenhouse indoor air temperature profile according to equation (1): the overall heat transfer coefficient of the greenhouse roof (U_o) and the ratio of evapotranspiration to solar radiation (α).

The vapour pressure deficit (VPD) was determined using the following empirical equation (Prenger and Ling, 2004).

$$VPD = 0.006412 \, (T_{ai}) - 0.03479 \, (RH), \quad kPa \qquad (5)$$

Where, T_{ai}, is the indoor air temperature in ºR (ºR = ºF + 459.67) and, RH, is the indoor air relative humidity in %.

A computer model has been developed and used for computing the total heat energy supply using the previous equation. The developed mathematical model has solved with the help of computer program based on MATLAB. The program requires two input files: one contains the simulation parameters and the other contains the input data. Table (1) lists all inputs required to run the program together with the parameter values used for the simulations runs. The program outputs data are also listed in Table (1). The simplified flowchart for MATLAB program showed in Fig. (2).

Table(1): Parameters and variables required as input and variables output by MATLAB program.

Configuration file inputs	**Value**
Floor surface area of greenhouse (A_f), m^2	32.00
Volume of greenhouse (V), m^3	87.70
Perimeter of greenhouse (P_r), m	24.00
Specific heat of indoor air (C_p), J kg^{-1} $^oC^{-1}$	1005.14
Overall heat transfer coefficient (U_o), W m^{-2} $°C^{-1}$	5.82
Air ventilation rate (V_a), m^3 s^{-1}	2.25
Ratio of evapotranspiration to solar radiation (α), dimensionless	0.48
Data file inputs	
Solar radiation inside the greenhouse (R_i), W m^{-2} Outdoor dry-bulb temperature (T_{ao}), °C Outdoor wet-bulb temperature (T_{aow}), °C Air temperature just leaving the cooling pads (T_{pad}), °C Indoor air temperature at the middle (T_{ai}), °C Indoor air temperature at the end (T_{aie}), °C Indoor air relative humidity (RH), % Density of indoor air (ρ), kg m^{-3}	
Data outputs	
Efficiency of evaporative cooling system (η), decimal Coefficient (A_1), °C Coefficient (A_2), m^{-1} Predicted indoor air temperature at the middle (T_{aipm}), °C Predicted indoor air temperature at the end (T_{aipe}), °C Vapour pressure deficit (VPD), kPa	

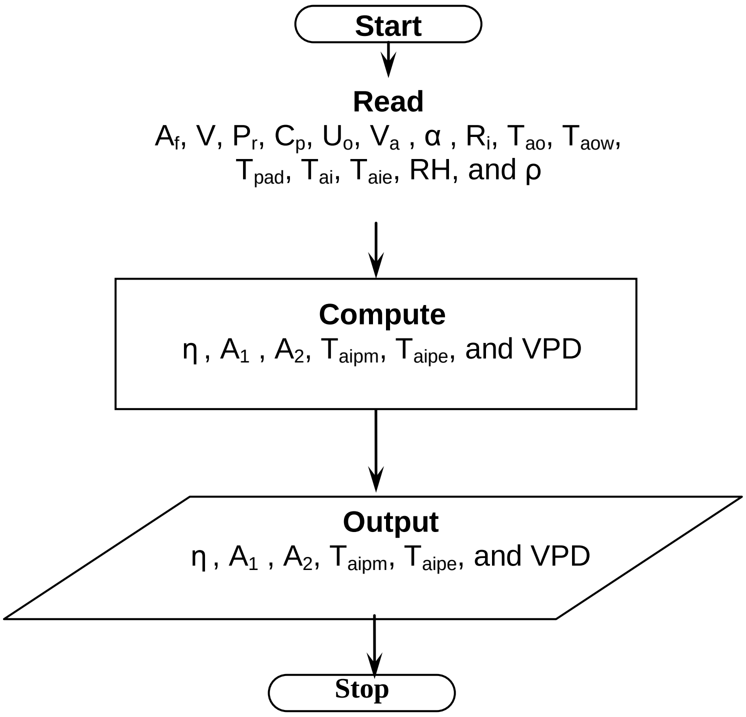

Fig. (2): Simplified flowchart for MATLAB program.

RESULTS AND DISCUSSION

Effectiveness of the evaporative cooling system based on fan-pad system under different circumstances was investigated in particular for the hottest days during the summer season (July and August of 2013). During this period the fan-pad system was automatically operated by the control board according to the optimal set point temperature (28°C). The first set of data was collected for calibrating of the model, from measurements performed during the experimental period. The daily averages hourly climatic conditions were selected for the calibration. Due to the experimental work executed on a nursery of sweet coloured pepper, it was assumed that there were no significant changes in the leaf area and in the physiological status of the seedlings. The daily average macroclimatic conditions (outside climate variables) during July and August months (average over the period 6.00 to 19.00 local time) are summarized and listed in Table (2).

Table (2): Daily average macroclimatic conditions and effectiveness of the evaporative cooling system during the experimental period

Month	T_{ao}, ºC	RH_o, %	T_{aow}, ºC	R_o, W m^{-2}	η, %
July SD	30.8 ± 0.7	48.6 ± 1.4	22.5 ± 0.25	593.7 ± 27.5	74.70 ± 1.6
August SD	31.1 ± 0.5	48.3 ± 1.7	22.7 ± 0.22	543.4 ± 31.0	78.57 ± 1.8

For the duration of the experimental period (two months), there were 834 hours of bright sunshine of which 772 hours (92.6%) were recorded and used in the model of the indoor air temperature gradients analysis and applications. The actual solar radiation recorded on the horizontal surfaces outside the greenhouse was always higher than that on the horizontal surface inside, due to the effective transmittance of cover (fiberglass) and the shading material (black net screen 50%) as revealed in **Fig. (3)**. Actual solar radiation data recorded outside and inside the greenhouse on a clear day ranged from near zero to about 1000 W m^{-2}. The lowest values during the experimental period were in the range of 35 – 75 W m^{-2}, which occurred just after sunrise and prior to sunset. They varied from day to another and during the month according to the weather conditions, solar altitude angle, and solar incident angle. The daily averages hourly solar radiation flux incident from sunrise to sunset on the horizontal surface outside and inside the greenhouse during July, respectively, were 593.7 and 258.5 W m^{-2}. Whereas, the actual solar radiation measured on August month, were 543.4 and 237.2 W m^{-2}, respectively, consequently, the transmittance of cover and shading black net caused in decreasing the actual indoor solar radiation intensity during that period by 56.46% and 56.35%, respectively.

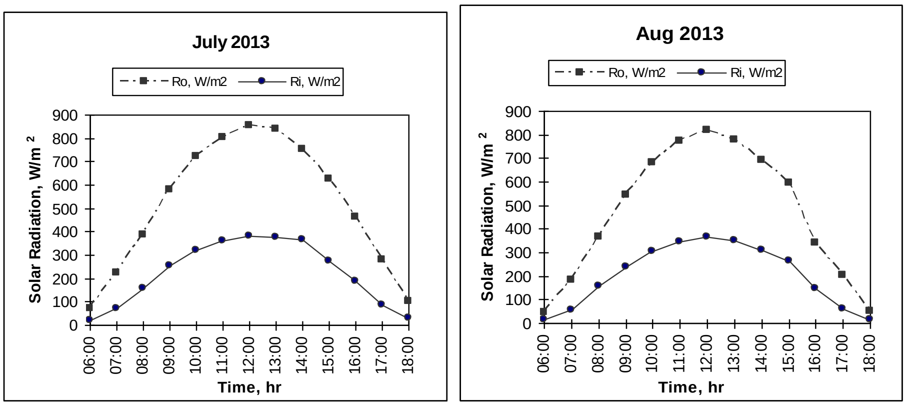

Fig. (3): Actual solar radiation data recorded outside (R_o) and inside (R_i) the greenhouse during July and August months.

The experimental data revealed that, the evaporative cooling system was able to keep the indoor air temperature lower than 28°C in all circumstances. In addition, the indoor air temperature stayed 8°C below outdoor air temperature, even during hot afternoons (temperatures higher than 35°C), due to the low levels of outdoor air relative humidity, high levels of air temperature, and accordingly the high efficiency of the evaporative cooling system (closest to 80%). Due to the short air stream path through the greenhouse (8 m), slight thermal gradients were observed in its direction. However, the findings of this research work will be assisted the designers when the long air path through the greenhouse (> 30 m) is available. **Fig. (4)** shows the measured and predicted indoor air temperatures at the middle of the greenhouse as compared with the outdoor air temperature during July and august. Gradual indoor air temperature rise from the cooling pads (24.6ºC) to the middle (27.0ºC), reaches 2.7ºC at and around noon when the solar radiation reaches its maximum value (374.8 Wm^{-2}).

The hourly variation of vapour pressure deficit (VPD) at the middle of greenhouse within the 24 hours during July and August is plotted in **Fig (5)**. It evidently appears that the VPD increases gradually after sunrise (0.578 kPa) till reaches the maximum value (1.770 kPa) afternoon. Vapour pressure deficit relates to the customary thinking about air relative humidity. Higher vapour pressure deficit (> 2.0 kPa) means that, the air surrounding the plant has a higher capacity to hold water, stimulating water vapour transfer (transpiration) into the air in this low air relative humidity conditions. Therefore, it has to be pointed out that the seedlings inside the greenhouse were not stressed. In reality, the VPD values during daylight were lower than 2.0 kPa, which correspond to no-heat stress conditions and water stress occurred, taking into account that the value of 2.0 kPa was mentioned by **Pringer and Ling (2004)** as the critical upper limit in order to avoid stomata closure. These circumstances were achieved by virtue of the evaporative cooling system effectiveness.

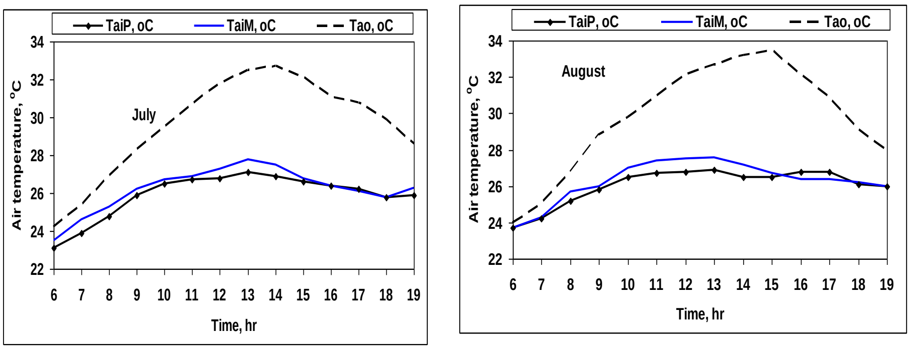

Fig. (4): Change in indoor air temperature (measured and predicted) and outdoor air temperature during July and August.

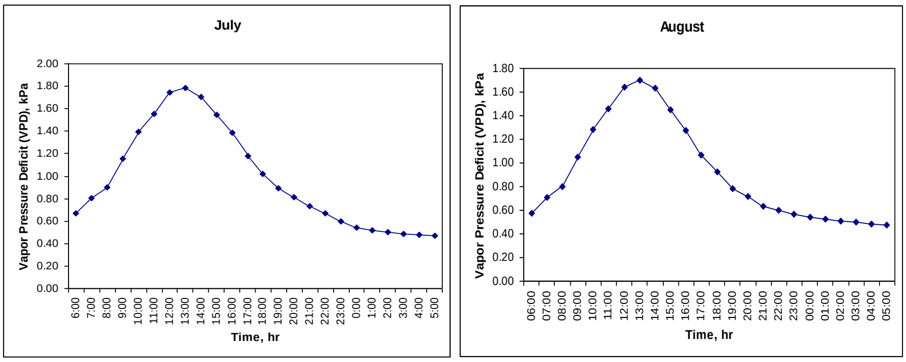

Fig.(5):Variations in vapour pressure deficit (VPD) inside the greenhouse during July and August.

The low value of VPD inside the greenhouse (0.475 kPa) occurred just prior to sunrise. Lower vapour pressure deficit, on the other hand, means that, the air surrounding the plant is at or near saturation, so the air cannot accept moisture from the leaf in this high air relative humidity condition. A computer model was used to calculate the air VPD inside the greenhouse during the experimental period by using the measurements of air temperature and air relative humidity surrounding the sweet pepper seedlings. Moreover, when the air VPD is too low (VPD < 0.43 kPa) at air relative humidity too high (RH > 80%) and air temperature very low (Ta < 14 °C), the water may condense out of the air onto leaves and other plant parts. This can provide a medium for fungal growth and diseases. Several studies were carried out by Pringer and Ling (2004) and Argus (2009) that explored disease pathogen survival at different climate levels revealed two critical values of air vapour pressure deficit.

The comparison between measured and predicted values of indoor air temperature at the middle of the greenhouse was then performed for a period of 3 successive days during July and August 2013. The measured and predicted values for the indoor air temperature in the middle of the greenhouse (nursery) are plotted in Fig.(6). This comparison was satisfactory as the coefficient of determination (R^2 = 0.987) was highly significant as revealed by the proximity of dots with the bisect line. Both factors (ventilation rate and shading) contribute to a more uniformity indoor air temperature distribution inside the greenhouse. More precisely, an air temperature rise of 3.5 t0 4.0ºC occurs between the cooling pads (inlet air) and the extracting fan (outlet air) under 2.25 m^3 s^{-1} ventilation rate. The smallest air temperature rise (1.8ºC) occurs early morning and prior to sunset when the intensity of solar radiation was low.

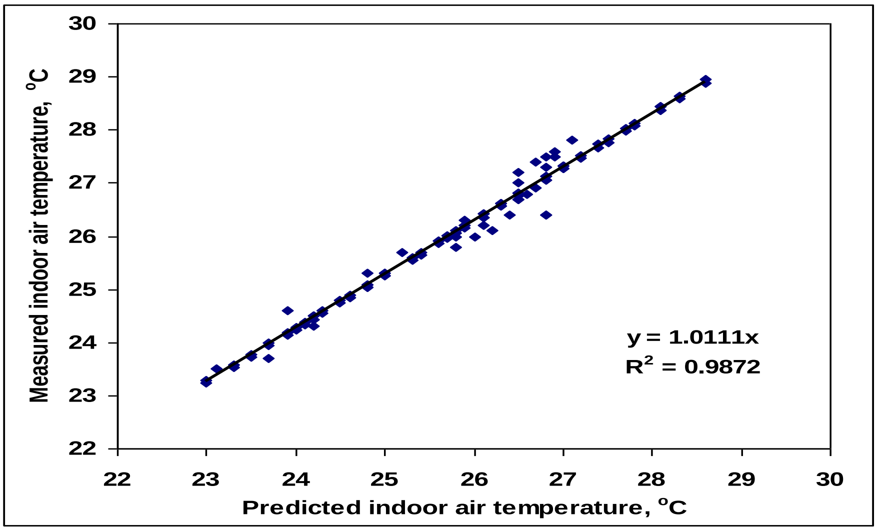

Fig. (6): Measured and predicted values for the indoor air temperature in the middle of the greenhouse (nursery). R^2 is the coefficient of determination.

After one week of the sweet coloured pepper seeds planting, seeds were emerged in the vegetative trays with 96.5% germination ratio as revealed in Fig. (7). Sweet pepper seedlings at four real leaves instance were transplanted inside the commercial greenhouses on 17th of August 2013 (the appropriate time for transplanting this crop during August 2013).

CONCLUSION

This research work tested and examined the parameters that influence the level of the obtained climatic conditions and their degree of uniformity in the shaded greenhouse (nursery) equipped with an evaporative cooling system based on fan-pad system. The hourly average actual solar radiation flux incident inside the shaded greenhouse during July and August 2013, respectively, was 593.7 and 543.4 W m^{-2}. While, the actual solar radiation measured outside the greenhouse at the same period was 258.5 and 237.2 W m^{-2}, respectively, consequently, the transmittance of cover and shading black net caused in reducing the actual indoor solar radiation during that period by 56.46% and 56.35%, respectively. The effectiveness of evaporative cooling was strongly affected by outdoor air temperature and relative humidity, therefore, the hourly average effectiveness of evaporative cooling during July and August was75.24% and 77.58%, respectively. Regulating the indoor climate for optimum conditions requires knowing the upper limits in terms of air temperature but also the limits of plant evapotranspiration rate in order to avoid plant heat stress, water stress, and stomata closer. A simple physical model, predicting the air temperature distribution inside the longitudinally ventilated greenhouse (nursery) was performed. The mode was calibrated and validated against the experimental data measured in the middle of the greenhouse, and a good agreement was obtained. The proposed model can be useful tool to study the performance of evaporative cooling systems for rational greenhouse design particularly the large one (commercial greenhouse). It also offers some elements that may help in improving the design of greenhouse cooling systems, such as ventilation rate, wet-pad, and fog-system.

Fig. (7): Seedlings of sweet colour peppers inside the nursery.

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تأثير نظام التبريد بالتبخير على الظروف المناخية لصوبة مشتل مظللة

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تم تنفيذ محاولة لتحليل نسبة الزيادة الحرارية التى تحدث فى الهواء الداخلى لصوبة صغيرة (مشتل) مظللة ومزودة بنظام تبريد بالتبخير (وسادة التبريد ومروحة سحب). تم إستغلال هذه الصوبة كمشتل لإنبات بذور محصول فلفل الألوان الحلو ونمو البادرات حتى الحصول على شتلات كاملة قابلة للشتل فى الصوب التجارية. إجريت التجارب تحت الظروف المناخية لجامعة المنصورة (شرق الدلتا خط عرض 31º 02' 41'' N وخط طول 31º 21' 55'' E وإرتفاع متوسط عن سطح البحر مقداره 16 M) خلال فصل الصيف لعام 2013م. لتوقع نسبة الزيادات فى درجة حرارة الهواء الداخلى لصوبة المشتل تم إقتراح نموذج مناخى بسيط يدمج تأثير كلاً من معدل التهوية وتظليل سقف الصوبة ومعدل البخر-نتح. لبيان صالحية النموذج المقترح للإستخدام، قياسات عديدة تم تنفيذها داخل الصوبة المظللة مثل درجة حرارة الهواء بعد وسائد التبريد مباشرة وفى منتصف الصوبة وعند مراوح السحب، كمية الأشعة الشمسية الساقطة داخل الصوبة، كفاءة نظام التبريد بالتبخير. البيانات التجريبية المتحصل عليها أوضحت أن نظام التبريد بالتبخير مع تظليل الصوبة كان قابل وكافى لتوفير درجة حرارة للهواء الداخلى للصوبة عند المستوى المرغوب لإنبات وإكثار بذور فلفل الألوان الحلو. تم تدقيق النموذج بإدخال البيانات المقاسة مع تلك المتحصل عليها من النموذج الرياضى عند منتصف الصوبة مع معامل تحديد مقداره 0.987. ونتيجة للمستوى الأمثل للظروف المناخية داخل الصوبة المظللة فقد بدء إنبات البذور بعد أسبوع واحد من زراعتها وبعد عشرة أيام وصلت نسبة الإنبات إلى 96.5% كما حدث نمو مثالى للشتلات حتى وصلت لمرحلة الشتل فى الصوب التجارية بعد ستة أسابيع من الإنبات.

قام بتحكيم البحث

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