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ORIGINAL ARTICLE

Impact of Foggy Cooling on the Greenhouse Microclimate

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ABSTRACT
A study was carried out to investigate the impact of water spraying via nozzles (foggy cooling) on the cooling efficiency of greenhouses using evaporative cooling systems. Two 9 m × 35 m greenhouses, equipped with a cooling pads system (evaporative cooling), were selected for this study. One of the two greenhouses was equipped with an additional set of six spray nozzles distributed along the greenhouse with a separation distance of 5 m. Readings of air temperature and relative humidity (RH) were recorded at three different locations within the greenhouses (at 0.5m from the pads, at the center of the greenhouse and at 0.5m from the suction fans).Observations were recorded at three heights, namely, 30 cm, 60 cm and100cm.The spray nozzles produced a good homogeneity in temperature across the greenhouse where they were fixed, with a mean temperature difference between the high and low values of2.4°C,compared to 5.5°Cin the greenhouse without the spray nozzles. The mean RH of 72% was observed in the spray nozzle-equipped greenhouse compared to a value of 63%in that without the spray nozzles. Results also indicated that the mean cooling efficiency of the standalone pads system was 63%, compared to 70% with the additional foggy cooling system. This demonstrates the ability of the spray nozzles to significantly improve the greenhouse microclimate.
Keywords;*Greenhouse, evaporative cooling, spray nozzles, foggy cooling*

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INTRODUCTION

Greenhouse cultivation is one of the best modern agricultural practices aiming at increasing agricultural production and improving the quality of the final product. Greenhouse technology have become necessary to overcome environmental problems, specially under arid regions of high temperatures and low relative humidity during summer. In general, greenhouses protect the plants against the changes of temperature, wind and rain [1].

By controlling the most important environmental factors for plant growth (e.g. temperature and relative humidity), the importance of greenhouses is to create an environment suitable for plant growth (especially vegetables and ornamental plants) during any season of the year, thus achieving the maximum possible return per unit area [2].

To overcome the problems of high temperature during the summer months, cooling has become the most vital requirement for the greenhouse plants. The development of an appropriate cooling system that provides the optimal climate for crop growth is a difficult task as the design is closely related to local environmental conditions. In addition, selection of an appropriate cooling system depends mainly on the cultivated crop, repair and maintenance, simplicity and economic feasibility of the system [3].

With the increasing demand for agricultural products such as vegetables (tomato, potato, etc.), the need has become urgent for their off-season production. Several attempts have been made in this regard, including the use of different types of evaporative cooling pads, to reduce the temperature and alter the relative humidity in greenhouses. However, their performance was not critically evaluated [4]. Evaporative cooling devices are highly efficient in arid regions during warmer times of the year [5]. The high efficiency of these devices in desert areas is due to the ability of hot and dry air to evaporate the water with high capacity [6]. Kittas *et al*. [7] investigated the performance of fan-pad system and reported an inside temperature reduction of 10°C compared the outside air temperature.

The use of a foggy system in green houses, which refers to a cooling system using a fine mist circulated through the greenhouse, is expected to help maintain optimal temperature and humidity, thus improving plant growth and productivity. This method is based on the fragmentation of the water mass and its transformation into a small fog range diameter 2–60 μm[8], in order to provide the largest surface area possible for air and water contact for the air stream to be cooled gradually. Most fog cooling systems are based on high pressure nozzles, which are inexpensive and are observed to provide high cooling efficiency compared to other systems [9]. The foggy system in a greenhouse is expected to lower air temperature and vapor pressure deficit, in addition to the lower crop transpiration and irrigation needs as a result of the high amount of water used in this system [10].

The purpose of this research was to evaluate the performance of the fog/mist cooling system coupled with the fan-pad system compared to the standalone fan-pad cooling system used in greenhouses. The performance assessment of the two systems was performed in terms of: (1) the temperature homogeneity inside the greenhouses and (2) the cooling efficiency of the cooling system.

MATERIAL AND METHODS

Study area

This study was carried out on two greenhouses in the Nopel Group Company farm located 45 kilometers southeast of Khartoum, the capital city of the Sudan(15°25'47.3"N 32°50'25.5"). The experimental work was performed during the summer season (mainly during May) of 2016.

Design features of the greenhouses and the measurement system

Two greenhouses, equipped with cooling pads systems, were selected for this study. One of the two greenhouses was equipped with additional spray nozzles to investigate their impact on the greenhouse microclimate. Observations, for RH and wet and dry temperatures, were recorded from outside and different inside locations of the greenhouses. Inside the greenhouses, measurements were taken from locations distributed longitudinally and transversally across the greenhouses at three heights (30 cm, 60 cm and 100 cm)as shown in **Figures1& 2.**Longitudinally, measurements were recorded at three different locations along the greenhouses at (1) 0.5m from the pads, (2) the center of the greenhouse and (3) 0.5m from the suction fans. Transversally, measurements were recorded at (1) 1.5 m from both sides of the greenhouses and (2) at the center of the greenhouses.

*T*he cooling pads

The cooling pads, used in the experimental greenhouses, were made from a loose perpendicular cellulose, which is commonly used for evaporative cooling. The cooling pads, with a complete cycle of cooling water, were installed vertically on the air inlets located on northern sides of the greenhouses. The dimensions of the pads were 6 m length × 2 m width× 20 cm thick (**Figures 2 & 3**). An electric pump, of 1.15kw capacity, was used to supply the water to the pads at a rate of 5 - 60 L/ min, with a sufficient pressure to reach the top of the pads.

The foggy cooling system

Six ventilating fans, moving 180 degrees on their perimeters, were mounted along the roof of the greenhouse at equal longitudinal distances between them(**Figure 4)**. The water came through the spray nozzles in a form of vapor at high-pressure and distributed by the fans. An electric pump, of 0.74-1.10 kW capacity and a frequency of 50-60Hz, was used to pump the water to the spray fans at a discharge rate of 0.72 - 2.90L/min. The pumped water reached the spray nozzles at a pressure of 0.51 MPa and left them at a pressure of 6.89MPa through the spray holes located within the fan area in a form of extra small droplets.

Data collection

At midday hours, the dry temperature was measured by placing the thermometer in a dry place to give the dry air temperature. When measuring wet temperatures, the thermometer was covered with a cloth dampened by water and exposed to the natural air stream. The corresponding RH values were determined using the Psychrometric Chart[11].

Cooling efficiency

Outside and inside climatic parameters were measured and used to estimate the evaporative cooling efficiency (μ). The cooling efficiency of the pads can be calculated by Equation (1) according to ASHRAE [12].

$$\mu_{p.cool} = \frac{T_o - T_{in}}{T_o - T_{wb}} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (1)$$

where, $\mu_{p.cool}$ is the cooling efficiency of the pads, T_o and T_{wb} are the dry and wet bulb temperatures (ºC) outside the greenhouse and T_{in} is the air temperature (ºC)just behind the pads.

The cooling efficiency of the fogging system, however, was determined using Equation (2)according to Li and Willits [1].

$$\mu_{f.cool} = \frac{T_{unfog} - T_{fog}}{T_{unfog} - T_{wbfog}} \dots\dots\dots\dots\dots\dots\dots\dots (2)$$

where, T_{fog} and T_{wfog} are the dry and wet bulb air temperatures (ºC)in the fogged greenhouse and T_{unfog} is the air temperature(ºC) in the un-fogged greenhouse.

RESULTS AND DISCUSSION

Descriptive statistics of the collected data

Table 1summarizes the descriptive statistics of air temperature and RH of the two greenhouses. Where, SD represents the standard deviation, CV the coefficient of variation and SE the standard error. While, Table 2 describes the distribution of temperature and RH across the two greenhouses. The results indicate that, the temperature and relative humidity varied between 28.8 ºC and 72%and 34.3 ºC and 53%, respectively, in the greenhouse without spray nozzles. In the greenhouse with spray nozzles, however, the temperature and relative humidity varied between 28.2 ºC and 76% and 30.6 ºC and 68%, respectively.

It was observed that the temperature values, in both the greenhouses, increased near the suction fans compared to the opposite side near the pads as shown in Tables 2 and Figures 5 & 6. On the other hand, the results showed that the vertical distribution of temperature values inside the greenhouses is slightly heterogeneous.In the absence of the spray nozzles the temperature values slightly increase from 30.7 ºC at 0.5m form the pads and reaches 33-34 ºC as far as we go towards the suction fans. While with spray nozzles, slight increase was observed from 28.8 ºC near the pads to the highest temperature value of 30.6 ºC near the section fans. In contrast, it was observed that the values of the relative humidity, in both the greenhouses, were high near the pads and gradually drop towards the center of the greenhouse to reach the lowest values near the suction fans. The results also indicated that there was temperature homogeneity inside the greenhouse under the influence of the spray. This was proved by the temperature difference of2.4°Ccompared to 5.5°Cin the greenhouse without spray effect.

The mean cooling efficiency of the pad system ($\mu_{p.col}$) used in the experiments of this study was calculated at 63%. However, the mean cooling efficiency of the pad system with the additional foggy system ($\mu_{f.col}$)was 70%. These results indicated that the foggy system improved the performance of the conventional pads system in reducing the air temperature, increasing the relative humidity and increasing the cooling efficiency.

Table 1; Descriptive statistics of temperature and RH data.

Description	Greenhouse without spray nozzles		Greenhouse with spray nozzles	
	Temperature (°C)	**RH (%)**	**Temperature (°C)**	**RH (%)**
Max	34.30	72.00	30.60	76.00
Min	28.80	53.00	28.20	68.00
Mean	32.11	63.00	29.71	72.00
SD	1.55	0.05	0.76	0.03
CV%	5.00	8.00	3.00	4.00
SE±	0.30	0.98	0.15	0.50

Table 2. The average dry (T) and wet (T_{wb}) temperatures and relative humidity (RH)across the two experimental greenhouses at an outside ambient temperature of 39.3 ºC, wet bulb temperature of 24.9 ºC and air temperature behind the pads of 30.2 ºC.

Greenhouse without spray nozzles				Greenhouse with spray nozzles			
Location	T (ºC)	T_{wb} (ºC)	RH (%)	Location	T (º C)	T_{wb} (ºC)	RH (%)
$L_1W_1H_1$	30.7	26.3	72	$L_1W_1H_1$	28.8	25.1	74
$L_1W_1H_2$	31.0		70	$L_1W_1H_2$	28.8		74
$L_1W_1H_3$	31.6		67	$L_1W_1H_3$	29.0		73
$L_1W_2H_1$	28.8	24.5	71	$L_1W_2H_1$	28.5	24.7	74
$L_1W_2H_2$	29.1		69	$L_1W_2H_2$	28.2		76
$L_1W_2H_3$	29.1		69	$L_1W_2H_3$	28.2		76
$L_1W_3H_1$	30.7	25.6	69	$L_1W_3H_1$	28.9	25.2	75
$L_1W_3H_2$	30.7		69	$L_1W_3H_2$	29.0		74
$L_1W_3H_3$	30.9		67	$L_1W_3H_3$	29.1		73
$L_2W_1H_1$	32.3	26.3	64	$L_2W_1H_1$	30.0	26.0	74
$L_2W_1H_2$	32.6		63	$L_2W_1H_2$	30.2		73
$L_2W_1H_3$	32.7		62	$L_2W_1H_3$	30.2		73
$L_2W_2H_1$	32.3	25.3	60	$L_2W_2H_1$	30.0	25.6	71
$L_2W_2H_2$	31.9		62	$L_2W_2H_2$	30.0		71
$L_2W_2H_3$	31.8		63	$L_2W_2H_3$	29.8		73
$L_2W_3H_1$	32.4	26.3	63	$L_2W_3H_1$	29.9	26.1	74
$L_2W_3H_2$	32.9		62	$L_2W_3H_2$	29.9		74
$L_2W_3H_3$	32.8		61	$L_2W_3H_3$	30.0		73
$L_3W_1H_1$	33.3	26.6	60	$L_3W_1H_1$	30.1	25.6	71
$L_3W_1H_2$	33.3		60	$L_3W_1H_2$	30.2		70
$L_3W_1H_3$	33.3		60	$L_3W_1H_3$	30.4		69
$L_3W_2H_1$	34.2	26.0	54	$L_3W_2H_1$	30.4	26.0	69
$L_3W_2H_2$	34.3		53	$L_3W_2H_2$	30.6		68
$L_3W_2H_3$	34.3		53	$L_3W_2H_3$	30.6		68
$L_3W_3H_1$	33.4	26.8	60	$L_3W_3H_1$	30.4	25.6	69
$L_3W_3H_2$	33.3		61	$L_3W_3H_2$	30.4		69
$L_3W_3H_3$	33.3		61	$L_3W_3H_3$	30.6		68

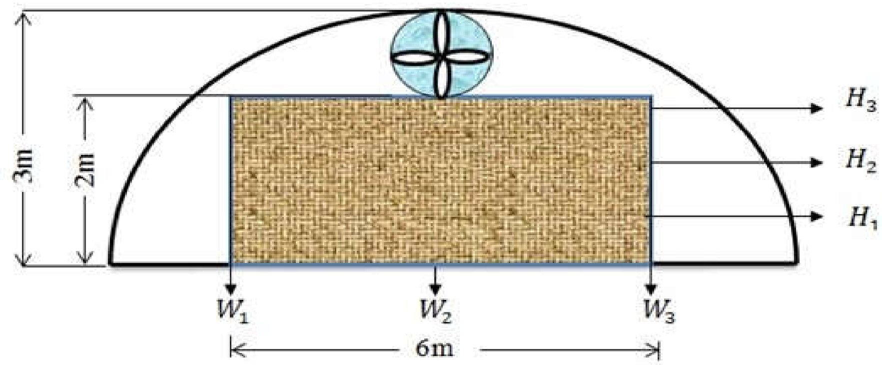

Figure1. The cross section of the greenhouse.

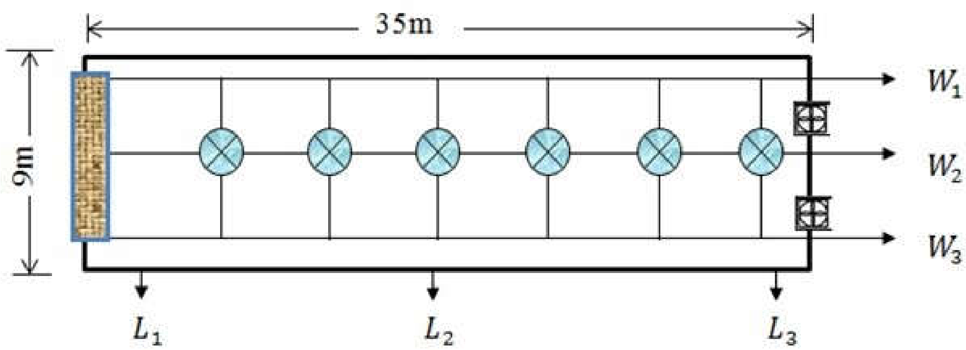

Figure2. The longitudinal section of the greenhouse.

Figure3; (a) the outward appearance and (b) the interior appearance of the pads.

Figure 4;Cooling system fans with spray nozzles mounted at the roof of the house.

Figure 5; Average temperature inside the greenhouse: with and without spray nozzles.

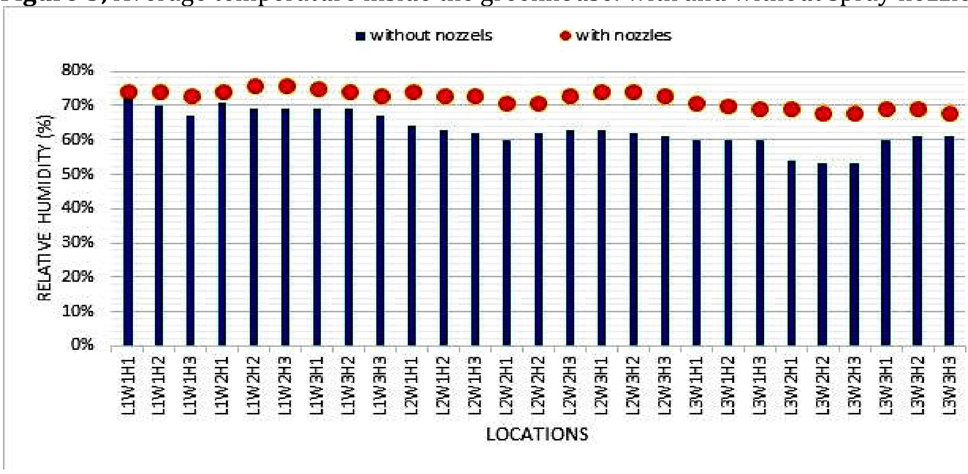

Figure 6; Average relative humidity inside the greenhouse: with and without spray nozzles.

CONCLUSION

This study was conducted to evaluate the performance of the foggy cooling system inside the greenhouses. The study relied on a comparison between two houses, one using spray system and the other without spray. The results of this study are summarized as follows:

- It was found that the temperature values inside the greenhouse with foggy cooling was homogeneous, with temperature difference of 2.4°C compared to5.5°C without spray effect.
- The relative humidity was high under the effect of spray (76%) compared to that without the spray (72%).
- The cooling efficiency improved under the effect of spray nozzles (70%)compared to that without spray nozzles (63%).

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