

Microclimate inside a Tropical Greenhouse Equipped with Evaporative Cooling Pads

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ABSTRACT

Tropical greenhouses require active evaporative cooling system such as pad-and-fan to ensure a suitable microclimate for crop production. Excess heat causes indoor temperature to become hotter than desired resulting in detrimental effects to crop growth and production. Solar radiation intensity and outside temperature affect temperature and relative humidity level inside a greenhouse, while wide gradients in temperature and relative humidity can cause problems related to crop growth and production uniformity. A 300 m² greenhouse, equipped with evaporative pad and four exhaust fans at each end walls, was used in the study. Horizontal and vertical profiles of the temperature and relative humidity inside the greenhouse were investigated. Results showed that temperature increased from evaporative pad area to exhaust fans area in a horizontal plane, while relative humidity showed an inverse pattern from temperature. In the vertical plane, temperature increased, while relative humidity decreased from lower level to the upper level. ANOVA results showed that in overall, temperature and relative humidity inside the greenhouse were uniform as there was no significant difference at 95% confidence interval. Thus, it was concluded that greenhouse cooling system by evaporative pad and exhaust fans are suitable for application in a tropical country such as Malaysia.

Keywords: Tropical greenhouse, pad-and-fan, temperature, humidity

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INTRODUCTION

Controlled environment in a greenhouse can provide suitable conditions for temperate vegetables and flowers to be grown optimally in Malaysian climate. In the tropics, the main constraints of crop production in the open

fields are extreme solar radiation, high rainfall, high humidity, insects and disease infestation (Hawa, 1990; Rezuwan, 2000). Excess heat in the greenhouse environment is considered a challenge in Malaysia, especially for lowland areas. This is because excess heat can cause indoor temperature to become much hotter than desired (Kittas, 2003) and thus, giving detrimental effects to crop growth and production. Malaysian climate, which is hot and humid, is not suitable for temperate crops and vegetables, causing Malaysia to import RM680 million worth of vegetables annually (Rezuwan, 2000). The major types of imported vegetables include high value temperate vegetables such as cabbage, cauliflower, broccoli, tomato and bell pepper.

Optimum temperature and humidity are essential in order to provide a suitable condition inside the greenhouse. Methods of reducing excess heat in a greenhouse are many. One is by natural ventilation, which lessens the amount of heat energy from the sun and also by shading (Miguel *et al.*, 1994; Hawa, 2006). Although ventilation is probably the simplest and cheapest way to reduce heat, the method is not efficient enough to reduce temperature inside the greenhouse in the tropical climate. Based on a study by Faisal *et al.* (2006), natural ventilation alone is not enough to reduce the temperature in a tropical greenhouse in Malaysia. Hence, additional cooling system is essential. One of the methods used to reduce the temperature inside a greenhouse is by evaporative cooling. In this method, as water evaporates, energy is lost from the air and the temperature is reduced (Simmons & Lott, 1996). In the Mediterranean region, evaporative cooling is desirable to prevent plant stress and produce marketable quality of crops (Hanan *et al.*, 1998).

The greenhouse in Malaysia requires cooling system to reduce the inside temperature. Most of the heat load inside the greenhouse comes from solar radiation (Walker, 1983). A major greenhouse operational cost comes from electrical consumption, whereby the cooling system contributes a significant part (Fang, 1995). Optimum temperature and humidity are essential in order to provide a suitable condition inside the greenhouse. Moreover, uniformity of temperature and humidity distribution inside a greenhouse are also crucial to gain more productivity in an effective way (Arbel *et al.*, 2003). Most previous studies on the greenhouse cooling system were carried out for temperate and dry areas. For instance, Kittas *et al.* (2001) presented sensible and latent heat profiles along a 60-m long greenhouse in Mediterranean area. It was reported that a 4°C rise in temperature is tolerated across the greenhouse (Nelson, 2003). However, data of the horizontal and vertical microclimate profiles inside the greenhouse with cooling pads in the tropical areas are rather limited.

This paper highlights a study on the evaluation of microclimate inside the greenhouse using the pad-and-fan cooling system. Both temperature and humidity profiles inside the greenhouse were evaluated in order to find uniformity of the cooling system.

EXPERIMENTAL SETUP

Study Area

The experiments were carried out at the Malaysian Agricultural Research and Development Institute (MARDI) in Serdang, Selangor. The Institute is located at the latitude 2°59' N and the longitude 101°42' E. A quonset shape greenhouse, galvanized steel tube with polyethylene covering material, equipped with the pad-and-fan evaporative cooling system, was used for the

study. The dimension of the greenhouse is 30 m in length, 10 m in width and 4.3 m in height. The greenhouse has an area of 300 m² and a volume of 1020 m³. The greenhouse elevation is 37.8 m above the mean sea level.

The covering material used for the greenhouse is a clear polyethylene thermic film. The film has a transmissivity value of more than 95% with U.V. stabilizer, anti-static and anti-condensation. Polyethylene (P.E.) is used as the covering material as it has low transmission coefficient compared to glass, which can reduce the amount of solar radiation heat transmitted inside greenhouse, and it is also less expensive compared to acrylic.

Cooling System

The cooling system adopted was the evaporative pad-and-fan type. Evaporative pads were attached at the end south-wall of the greenhouse (Fig.1). Ambient air was forced through a 9-m width by 2-m height and 1.5-mm thick, wet cellulose cooling pads of the 10-m wide south-wall. The pads have 85% humidification efficiency as claimed by its manufacturer, with 50 Pa pressure lost at 2.0 m s⁻¹ air velocity. Evaporative pads were operated only during daytime from 9 am to 5 pm. During night time, the system was switched off to avoid excess moisture inside the greenhouse, as well as to avoid pathogen and disease problems. As air flows past the moist pad surfaces, some of the moisture evaporates into the air stream. The cool air from the pads flows across the 30-m length of the greenhouse before it is being exhausted by the fans placed at the opposite end of the north wall.

The diameter of each fan is about 1.2 m, using 1.12kW with 750 cubic meters per minute (cmm). Louvers will close when the fans shut down to avoid insects from getting into the greenhouse. The distance between each fan is 1.5 m and it is placed 1 m above the ground (Fig.2). These heavy duty welded steel frames have belt driven panels for low speed operation. Different fans are used each day to reduce wear, overrelative humidity eating and machine failure. The cooling system is controlled by a control panel, where the cooling stage can be set up to run either automatically or manually.



Fig.1: Evaporative pad constructed at the south wall of the greenhouse



Fig.2: Exhaust fans placed at the north wall of the greenhouse

METHODOLOGY

Sensors and Equipment

WatchDog 2000 series weather stations (Fig.3) are used for the greenhouse setup to provide real-time, local weather information and enable monitoring site-specific growing condition. One unit was placed outside the greenhouse located at the north side, and the other unit was put at the centre of the greenhouse. The weather stations are meant for measuring temperature, relative humidity, rainfall, solar radiation, wind speed, and wind plane. Measurement interval was selected from 1, 10, 15, 30, or 60 minutes. A 30-minute interval was selected to record the microclimate for 183 days before the station's memory is full. An LCD screen displays current and high or low readings. It is able to review the past 30 days' data and to confirm that the station and sensors are functioning. Built-in data logger that stores measurements in a file-safe, non-volatile memory gives an ideal solution to collect data without having the researcher present at the site during the period of the experiment or study. These data were then transferred into a PC via direct PC interface cable.



Fig.3: WatchDog weather station

Spectrum’s solarimeter was used to measure solar radiation intensity. The sensor sub-samples solar radiation between 300 and 1100 nanometers. The solarimeter was positioned in an appropriate area, without being shadowed or blocked by any other sensor or structure.

In order to determine the temperature and humidity profiles and gradients inside the greenhouse, temperature and humidity sensors incorporated into the WatchDog 200 Series Data Logger (Fig.4) were placed horizontally and vertically inside the greenhouse at a height of 1.0 m above the ground. The data logger sensor provides two sensor channels with a capacity of 7000 measurements. This sensor is mounted in an aspirated enclosure to avoid direct effects from solar radiation and high air velocity.



Fig.4: WatchDog 2000 Series data logger

Location of the Sensors

The length of the greenhouse was divided into three designated areas, namely, pad area (0-10 m), middle area (11-20 m) and fan area (21-30 m) (see Table 1). There were eight sensors to collect data on the temperature and humidity inside the greenhouse and one weather station to collect data on the temperature, humidity, solar radiation, and wind speed outside the greenhouse every 30-minute interval. All the above measurements were recorded on a data logger system. The greenhouse was empty with no crops planted. Six sensors were installed horizontally along the middle of the greenhouse, with 5 m distance from pad to fan (see Fig.5). Using the Cartesian coordinate system, these sensors were placed at (0, 5) - Sensor 1, (5, 5) - Sensor 2, (10, 5) - Sensor 3, (15, 5) - Sensor 4, (20, 5) - Sensor 5, and (25, 5) - Sensor 6. In the vertical plane, 3 data loggers were placed at 0.3 m (Sensor A), 1.0 m (Sensor B), and 2.5 m (Sensor C) from the ground (Fig.6) to refer to the low, middle and top positions. The sensors in the vertical plane were located at the centre of the greenhouse, i.e. at (15, 5) in the Cartesian coordinate. For the purpose of this study, a 60-minute interval (1 hour) was selected and data collection was running for two months.

TABLE 1
Area segment and representation

<i>Area</i>	<i>Segment (m)</i>	Represent
Pad	0-10	Cool area
Middle	11-20	Medium area
Fan	21-30	Warm area

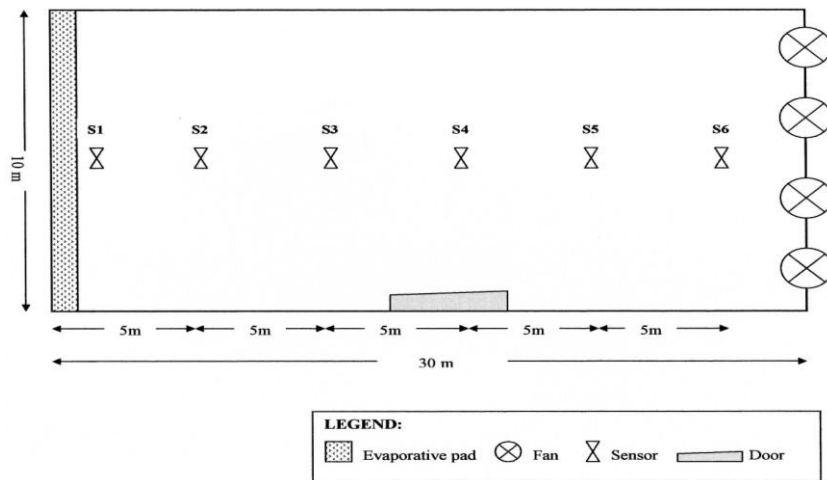


Fig.5: Greenhouse floor plan of the sensors in a horizontal plane

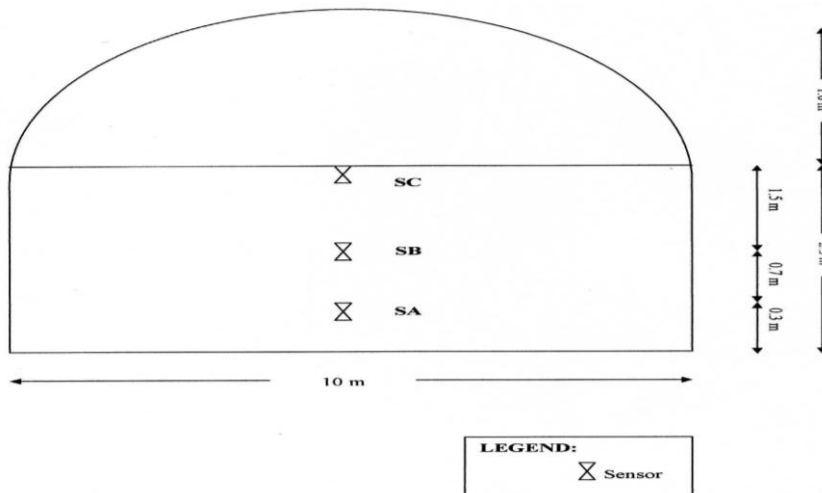


Fig.6: Greenhouse side plan of the sensors in a vertical plane

RESULTS AND DISCUSSION

Inside Temperature versus Outside Temperature

Fig.7 shows that the temperature inside the greenhouse increased when the temperature on the outside increased, and this increment was with a regression coefficient of 0.996. This was an average temperature from eight sensors. The result suggests that with the increase in the ambient (outside) temperature, heat transfer into the greenhouse also increased and led to an increase in the temperature inside the greenhouse. The highest average temperature inside the greenhouse was 33.0°C. The general regression equation for the relationship between temperatures inside and outside the greenhouse shown in the graph can be formulated as follows:

$$\text{Inside temperature} = 0.9976 * [\text{Outside temperature}] - 0.0129; R^2 = 0.996$$

Inside Relative Humidity versus Outside Relative Humidity

The relationship between inside relative humidity and outside relative humidity is shown in Fig.8. This is the average humidity taken from eight sensors. The results show a linear relationship between inside and outside relative humidity with a strong correlation of $R^2=0.997$, and an average inside relative humidity of 53.6%. The general regression equation for the graph is formulated as follows:

$$\text{Inside relative humidity} = 1.064 * [\text{Outside relative humidity}] - 8.2844; R^2 = 0.997$$

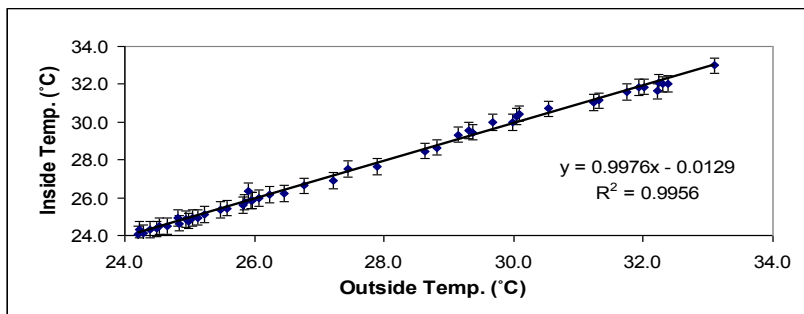


Fig.7: Inside temperature versus outside temperature in the greenhouse

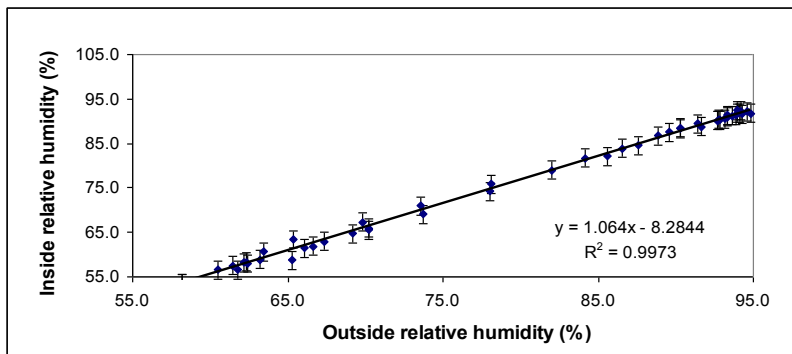


Fig.8: Inside relative humidity versus outside relative humidity

Temperature and Relative Humidity inside the Greenhouse versus Time

The hourly variation of the vertical temperature profile inside the greenhouse is shown in Fig.9. Each sensor showed that the temperature started to increase from 8:30 am and achieved the peak value at 14:00 pm, before it decreased until 20:00 pm. The average day temperature (7.30 am – 6.30 pm) inside the greenhouse is 30.7°C, which is lower than the average outside temperature, with the mean of cooling system (Table 2). Meanwhile, the average night temperature (7.00 pm - 7.00 am) is 25.7°C, indicating that the outside temperature is much lower than the inside temperature because the evaporative pad system was not running to avoid high relative humidity in the greenhouse. However, the average temperature inside the greenhouse during the night is acceptable for crops.

TABLE 2

Average temperature and relative humidity inside and outside the greenhouse at vertical plane

	Average Day Temperature (°C)	Average Night Temperature (°C)	Average Day Relative Humidity (%)	Average Night Relative Humidity (%)
Inside Greenhouse	30.7	25.7	71.2	83.5
Outside Greenhouse	31.1	25.4	68	87.6

Fig.10 shows the hourly variation of vertical inside relative humidity in an empty greenhouse. Each sensor showed that the relative humidity started to decrease from 8:30 am and achieved the lowest value at 14:00 pm. Then, the relative humidity started to increase through the day. This showed that during the morning and night, the humidity inside the greenhouse was high as the environment was condensed with vapour. When solar radiation intensity got higher, much of the vapour started to evaporate causing lower relative humidity. The average day relative humidity (7.30 am – 6.30 pm) inside the greenhouse is higher than average outside relative humidity with the mean of cooling system (Table 2). The average night relative humidity (7.00 pm- 7.00 am) shows that outside relative humidity is not much different than the inside relative humidity because the evaporative pad system was not running to avoid the high relative humidity in the greenhouse.

The average day temperature (7.30 am – 6.30 pm) inside the greenhouse at horizontal plane is 32.1°C, which is higher by 3.1% from the average outside temperature through the cooling system. This shows that the cooling system is insufficient to reduce the temperature inside the greenhouse in the horizontal plane to the range of 24 - 30°C. Hence, more fans are needed to be run so as to decrease the temperature through convection heat transfer. The average night temperature (7.00 pm - 7.00 am) is 26.2°C, indicating that the outside temperature is much lower by 3.8% than the inside temperature because the evaporative pad system was not running to avoid the high relative humidity in the greenhouse (Table 3). However, the average temperature inside the greenhouse during night time is acceptable for crops.

In Fig.11, each sensor showed that relative humidity started to decrease from 8:00 am and achieved the lowest value at 13:00 pm. Relative humidity then started to increase through the day. Relative humidity inside the greenhouse was comparatively lower than ambient relative humidity. The graph also shows an inverse pattern with the graph of temperature versus time (Fig.12), whereby relative humidity was at the lowest value when the temperature achieved the peak value. This result supports the theory that relative humidity has an inverse relationship with temperature. Table 3 summarizes the average relative humidity inside and outside the greenhouse during at day and night times. It shows that the inside relative humidity at day time is lower than the outside relative humidity by 11.8% and at night time, the relative humidity inside the greenhouse is also lower than the outside by 4.1%.

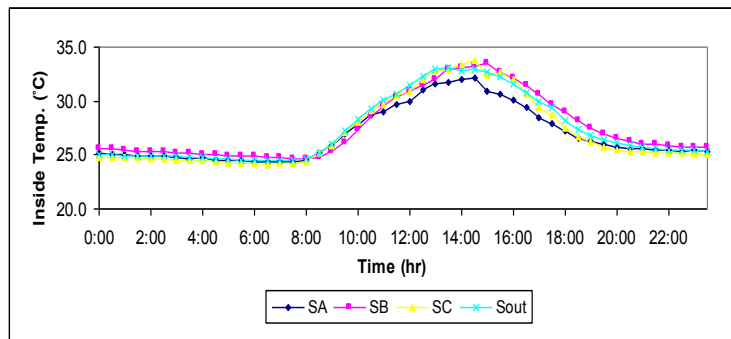


Fig.9: Changes in the vertical temperature profile with time inside the greenhouse. A represents low sensor, B represents middle sensor and C represents top sensor

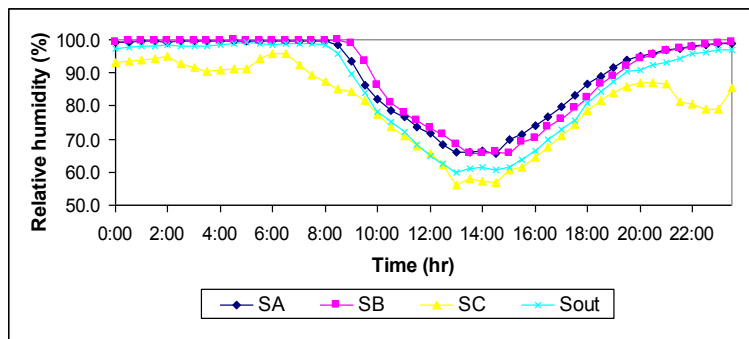


Fig.10: Changes in the vertical relative humidity profile with time inside the greenhouse. A represents low sensor, B represents middle sensor and C represents top sensor

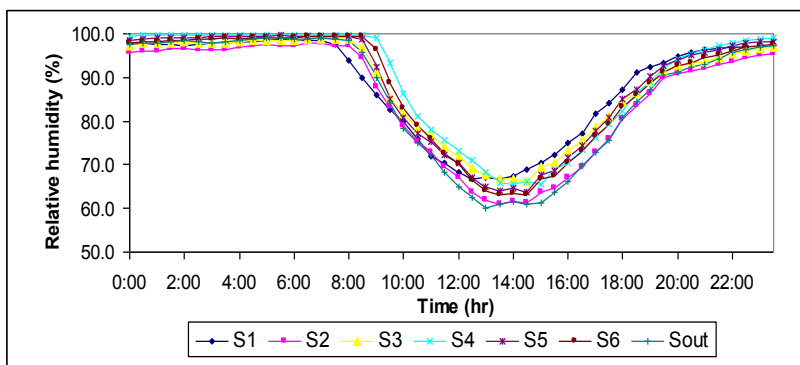


Fig.11: Changes in the horizontal relative humidity profiles with time inside the greenhouse

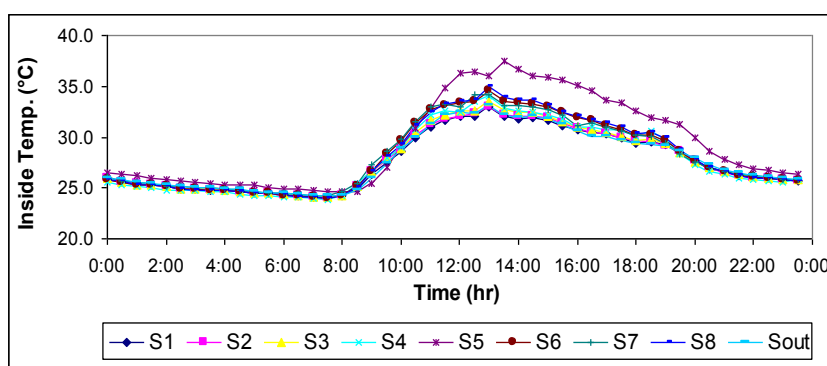


Fig.12: Changes in the horizontal temperature profile with time inside an empty greenhouse

TABLE 3

Average day and night temperature inside and outside the greenhouse at horizontal plane

	Average Day Temperature (°C)	Average Night Temperature (°C)	Average Day Relative Humidity (%)	Average Night Relative Humidity (%)
Inside Greenhouse	32.1	26.2	56.2	83.5
Outside Greenhouse	31.1	26.1	68	87.6

Vertical Temperature and Relative Humidity inside the Greenhouse

There were three temperature sensors placed in the vertical plane of the greenhouse at 0.3 m (Sensor A), 1.0 m (Sensor B) and 2.5 m (Sensor C) height. As shown in Fig.13, Sensor C had the highest average temperature (27.55°C), followed by Sensor B (27.10°C) and Sensor A (26.85°C). This shows that the convection heat transfer was from the lower level to the upper level as hot air moves to a higher altitude when it gets more energy and less density, especially when solar radiation is high. The temperature recorder at 2.5 m height (SC) was higher than the ambient temperature by 0.9°C at 14:00 hr, while at the temperature at the bottom level of the greenhouse (0.3 m – SA) was lower than ambient temperature by 0.8°C. Sensor C (SC) received higher solar radiation intensity compared to the bottom level and thus had the highest temperature than Sensors A and B. From the ANOVA results, the difference between each point in each hour was found to be insignificant as $F < F_{crit}$ at 95% confidence interval (Table 4). This was because the greenhouse was a closed system, and this caused it to have more uniform temperature between each elevation.

Fig.13 illustrates that Sensor C had the lowest relative humidity (80.56%), followed by Sensor B (89.1%) and Sensor A (89.21%). These results show that relative humidity has an opposite pattern from temperature as it will decrease relative humidity increases. Table 5 shows the ANOVA result on each sensor, where it reveals the significant difference within each sensor with p-value less than 0.05.

Horizontal Temperature and Relative Humidity inside the Greenhouse

Fig.14 shows that the temperature inside the greenhouse was much higher near the exhaust fan area (26.8°C), followed by the middle area (26.5°C) and near the evaporative pad area (25.9°C). This confirmed that the temperature increased along the greenhouse from the evaporative pad to the exhaust fan due to solar heat gain. Nevertheless, the ANOVA results show no significant difference in the temperature in each area as $F < F_{\text{critical}}$ with p-value=0.09 at 95% confident interval (Table 6). Meanwhile, temperatures near the evaporative pad are cooler than the outside temperature by an average of 1°C, while the temperature in the middle of the greenhouse is hotter than the outside temperature by 5°C. This proves that the temperature increases from the evaporative pads to exhaust fans as a result of conduction and radiation heat transfer. Similar trends have also been observed by Montero *et al.* (1981), Kittas *et al.* (2001), and Al-Helal (2006).

Fig.14 also shows that relative humidity inside the greenhouse is much higher near the evaporative pad area (82.8%), followed by the middle area (82.3%) and near exhaust fans area (80.9%). This confirms that relative humidity decreases along the greenhouse from the evaporative pad to the exhaust fan due to solar heat gain which reduces moisture content inside the greenhouse. The data were statistically analyzed and the ANOVA results are summarized in Table 7. The findings show that the relative humidity between each area is not significant where $F < F_{\text{critical}}$, with p-value = 0.39 at 95% confidence interval. This means that there is no significant difference in the relative humidity between each location.

Meanwhile, the ANOVA results show that the temperature inside the greenhouse in the vertical and horizontal planes has no significant difference at 95% confidence interval (Table 9). It also shows that relative humidity in the vertical plane is significantly different between each sensor (Table 10).

TABLE 4
Distribution and ANOVA for inside temperature between sensors in vertical plane

Groups	Count	Sum	Average	Variance
Sensor A	48	1288.94	26.85	6.31
Sensor B	48	1300.96	27.10	10.04
Sensor C	48	1322.34	27.55	8.68

Source of Variation	SS	df	MS	F*
Between Groups	11.923	2	5.96	0.71
Error	1176.247	141	8.34	
Total	1188.171	143		

* insignificant at 0.05 probability level

TABLE 5
Distribution and ANOVA for inside relative humidity between sensors in vertical plane

Groups	Count	Sum	Average	Variance
Sensor A	48	4282.2	89.21	153.04
Sensor B	48	4279.94	89.17	161.69
Sensor C	48	3867.11	80.56	151.38

Source of Variation	SS	df	MS	F**
Between Groups	2380.05	2	1190.03	7.66
Error	21907.57	141	155.38	
Total	24287.62	143		

** significant at 0.05 probability level

TABLE 6
Distribution and ANOVA for inside temperature between sensors in horizontal plane

Groups	Count	Sum	Average	Variance
Pad	48	1244.11	25.92	2.11
Middle	48	1274.01	26.54	3.84
Fan	48	1285.21	26.78	5.36

ANOVA

Source of Variation	SS	Df	MS	F*
Between Groups	18.82	2	9.41	2.49
Error	531.85	141	3.77	
Total	550.67	143		

* insignificant at 0.05 probability level

TABLE 7
Distribution and ANOVA for inside relative humidity between sensors in horizontal plane

Groups	Count	Sum	Average	Variance
Pad	48	3972.06	82.75	38.66
Middle	48	3987.51	83.07	85.60
Fan	48	3876.73	80.77	111.99

ANOVA

Source of Variation	SS	df	MS	F*
Between Groups	149.98	2	74.99	0.95
Error	11103.67	141	78.75	
Total	11253.64	143		

* insignificant at 0.05 probability level

TABLE 8
ANOVA statistical test for inside temperature factors

Regression Statistics						
R Square		0.992				
Standard Error		0.184				
Observations		47				

	df	SS	MS	F	Significance F	
Regression	3	189.074	63.025	1864.996	1.56657E-45	
Residual	43	1.453	0.034			
Total	46	190.527				

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	3.8454	0.708	5.428	2.46E-06	2.417	5.274
Outside temperature (X1)	0.8309	0.028	29.451	3.88E-30	0.774	0.888
Solar radiation (X2)	-0.0024	0.0003	-6.320	1.25E-07	-0.003	-0.002
Rainfall (X3)	-0.0352	0.049	-0.705	0.485	-0.135	0.065

TABLE 9
ANOVA for temperature inside the greenhouse between sensors

Inside Temperature	F	F _{critical}	p-value
Vertical plane	2.49	3.06	0.49
Horizontal plane	1.35	2.03	0.23

TABLE 10
ANOVA for relative humidity inside the greenhouse between sensors

Inside Relative Humidity	F	F _{critical}	p-value
Vertical plane	0.95	3.06	<0.001
Horizontal plane	1.42	2.03	0.19

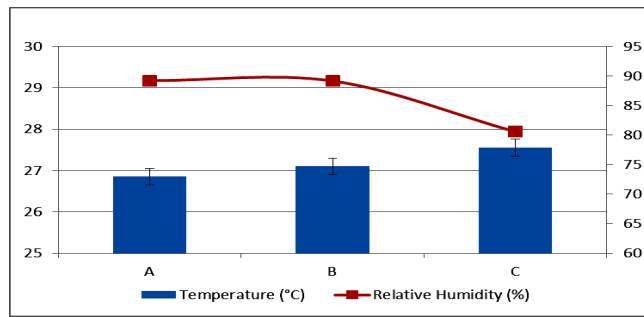


Fig.13: Inside temperature and relative humidity at vertical plane. A represents low sensor, B represents middle sensor and C represents top sensor

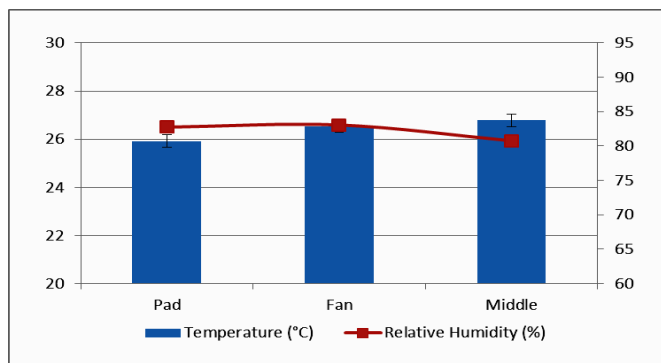


Fig.14: Inside temperature and relative humidity at horizontal plane

Inside Temperature versus Solar Radiation

Solar radiations outside the greenhouse gave a direct impact on the temperature inside the greenhouse due to radiation heat transfer process. Fig.15 shows linear relationships between the inside temperature and solar radiation, with a good regression coefficient of $R^2 = 0.77$. This result suggests that solar radiation heats up the greenhouse and increases heat transfer through radiation which leads to the temperature increase inside the greenhouse.

$$\text{Inside temperature} = 0.0179 * \text{Solar radiation} + 26.652$$

Inside Temperature versus Rainfall Intensity

Rainfall intensity shows low correlation with the temperature inside the greenhouse. Fig.16 shows low regression coefficient with $R^2 = 0.14$. This concludes that the cooling effect by rainfall is not enough to reduce the temperature inside the greenhouse.

$$\text{Inside temperature} = 5.2483 * \text{Rainfall intensity} + 28.982$$

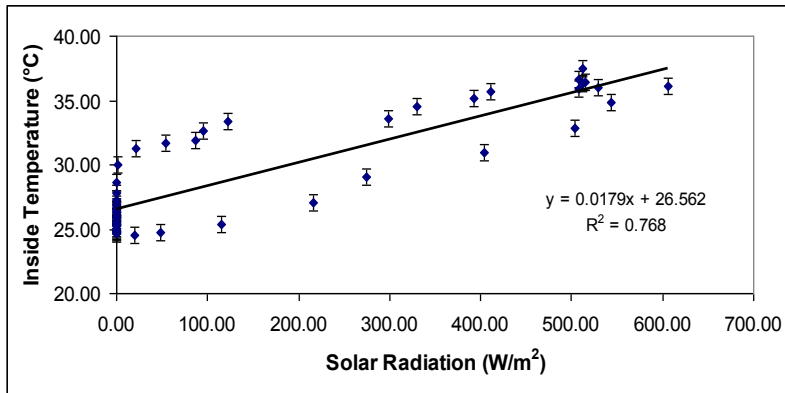


Fig.15: Inside temperature versus solar radiation

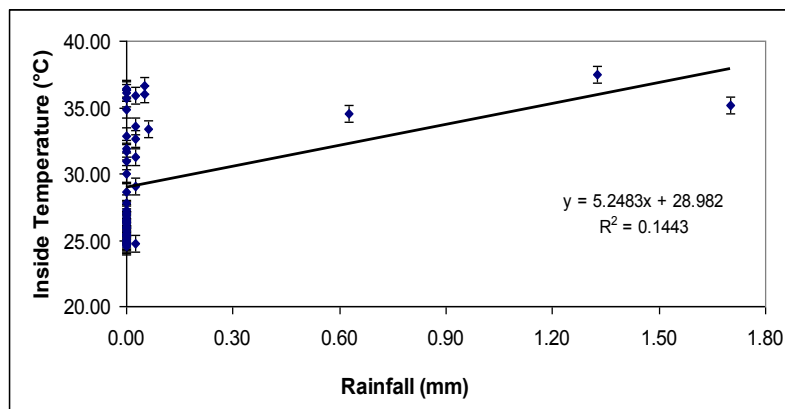


Fig.16: Inside temperature versus rainfall

Results of the Analysis of Variance (ANOVA) are presented in Table 8. The regression value between the outside temperature, solar radiation and rainfall with the inside temperature is 0.992 and the standard error is 0.184. These show that the outside temperature and solar radiation have p-value less than 0.05, while rainfall has p-value = 0.484622 > 0.05. Hence, it is concluded that rainfall has less effect on the temperature inside the greenhouse.

CONCLUSION

The temperature inside the greenhouse increased from early morning until afternoon and then started to decrease until night time. The graph pattern of the inside temperature versus time is significantly similar with the graph of the solar radiation versus time due to the increase in temperature when solar radiation intensity increases. In the vertical plane, the temperature at the upper level (2.5 m) was found to be higher, followed by the temperature at the middle (1.0 m) and bottom levels (0.3 m). These results support the theory that hot air moves from lower level to upper level. However, since the greenhouse was fully covered, greenhouse pressure driven flow produced by convection was unlikely to differ at each level.

The temperature gradient was much obvious when the solar radiation intensity was high and the outside temperature was at the maximum in the day. Meanwhile, the inside temperature had a linear relationship with the outside temperature, with a strong regression coefficient. This concludes that the temperature inside the greenhouse with evaporative cooling system and exhaust fans can give uniform conditions inside the closed greenhouse.

Relative humidity values inside the greenhouse show opposite trends from temperature. In the vertical plane, relative humidity value at the upper level (Sensor C) was lower than at the middle (Sensor B) and bottom levels (Sensor A) of the greenhouse. In the horizontal plane, relative humidity inside the greenhouse decreased from near the evaporative pad to the exhaust fans. These results support the theory that relative humidity has an inverse relationship with temperature. Relative humidity inside the greenhouse was shown to be higher than outside the greenhouse as evaporative pads had added in moisture inside the greenhouse.

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