

PAPER 19 – EVALUATION OF THE THERMAL ENVIRONMENTS OF TWO SINGLE-SPAN TRIPLE-LAYERED GREENHOUSES EQUIPPED WITH CIRCULAR AND HORIZONTAL AIRFLOW FANS

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ABSTRACT

The microclimate of indoor production systems is highly dependent on the macroclimate of the ambient. As a result, the microclimate fluctuates with time with respect to the macroclimate and eventually making it have higher measurable climate parameters than the macroclimate. This study was carried out at Sangju Smart Farm Innovation Valley, Sangju-si to compare and analyse changes in the thermal environment in two adjacent single-span tunnel greenhouses covered with two layers of polyethylene films (200 µm thick) and a layer of thermal curtain (3.5 mm thick). While one greenhouse was equipped with five circular airflow fans (HUMITEM-GH), the other had five horizontal airflow fans (Conv-GH). The *Seolhyang* variety of strawberries was used as the test crop. The greenhouse temperature (T_a), relative humidity (RH), vapour pressure difference (VPD), solar radiation (SR), and carbon dioxide (CO_2) data were collected using standard methods and data was analysed using MINITAB software. The statistical tools used for data analysis were descriptive statistics, analysis of variance (ANOVA), and t-Test. The total yield and marketable yield in the HUMITEM-GH was higher than the Conv-GH by 116.33 kg and 97.69 kg, respectively. There were significant differences between the two greenhouses microclimate both in the daytime and night-time with the HUMITEM-GH having higher and near-optimal climate parameters. This result has shown that the newly developed HUMITEM air circulation fan has a superior air circulation and flow capability than the conventional air circulation fans. This information may be of interest to farmers, horticulturists, and researchers who are involved in protected vegetable production.

KEYWORDS: CAF; HAF; HUMITEM; air-circulation; distribution; airflow

1. INTRODUCTION

A greenhouse is an indoor cropping system that allows the manipulation and control of environmental, nutrition, and biological variables. Additionally, it makes it possible to implement management techniques for successful crop production. Regardless of the unfavourable external conditions that may exist at the location, a variety of ornamental, food and cash crops can be cultivated steadily indoors. Throughout the growing season, the ideal indoor microclimate necessary for crop growth and development must be maintained (Iddio *et al.*, 2020; Ogunlowo *et al.*, 2022). Indoor cultivation is a widely accepted technique that has been adopted by small-, medium- and large-scale farmers with an estimated 5,630,000 hectares of protected agriculture all over the world as of 2019 (Hickman, 2019). Averagely, more than two countries per continent are engaged in greenhouse crop production and more than 60 countries where greenhouse commercial production is practised. Indoor cultivation has numerous advantages namely the ability to control the indoor thermal environment, protect against pest infestation and disease attack, multiple cropping, Off-season cropping, increased crop productivity per unit land area and labour, vertical cropping technology, guarantee food security, maximize high-quality products while minimizing production cost and increased water and chemical use efficiency (Katsoulas and Stanghellini, 2019). Despite the numerous benefits of indoor agriculture, there are some drawbacks namely high initial investment, and a shortage of greenhouse-specific tools and machinery (Reddy, 2016).

The internal microclimate of a greenhouse is primarily influenced by the climatic conditions of the surrounding environment. As a result, to achieve optimal crop production within the greenhouse, the microclimate in terms of light level (SR), air temperature (T_a), soil temperature (T_s), relative humidity (RH), and carbon dioxide (CO_2) must be manipulated to the recommended ranges for specific crops (Akpenpuun and Mijinyawa, 2020). Adequate

control strategies are required to keep the environmental variables within the optimum limits because these variables directly influence the efficiency of the cultivation system in terms of yield and expended energy either for cooling or heating (Yang *et al.*, 2022). Several studies have been conducted to investigate the impact of greenhouse microclimate parameters such as temperature, vapour pressure deficit, relative humidity, carbon dioxide concentration soil temperature, and solar radiation level and have shown that ranges of these parameters outside the optimum harm crop growth, development, and yield (Sim *et al.*, 2020; Kim *et al.*, 2022). Multiple cooling strategies can be used in greenhouses to provide an appropriate microenvironment including (i) shading methods such as applying whitewash or plastic nets or thermal screens, (ii) fans-pads evaporative cooling systems, fogging and evaporative roof cooling, and (iii) ventilation systems such as forced ventilation, using air circulation fans in combination with natural ventilation through sidewalls and roof vents as ventilation aids even distribution of climatic variables (Shamshiri *et al.*, 2018).

In the greenhouse, airflow is restricted by the structural members, plants, and equipment, resulting in a sharp increase in indoor temperature. Therefore, knowing the behaviour of meteorological elements, such as temperature, RH, VPD, SR, and CO₂ in a greenhouse, is essential to exploiting the benefits of protected cultivation. To achieve the optimal comfort level indoors in terms of T_a, RH, VPD, SR, and CO₂ appropriate climate control pieces of equipment are needed. Even though, there are several fans (different sizes and power ratings) for the greenhouse industry the choice of a particular circulation fan depends on the greenhouse's size, design, and desired environmental condition. As the air moves inside the greenhouse environment, gradients of these meteorological elements are formed throughout the structure and can result in a heterogeneous microclimate, which may be undesirable for plants (Cesar *et al.*, 2021). In addition to these parameters, it is also important to monitor and control pests and diseases, as well as maintain proper soil moisture and nutrient levels. Regular monitoring and adjustments to the greenhouse environment would help ensure the optimal growth and productivity of plants. The objectives of this study were to compare and analyze changes in the thermal environment of two tunnel greenhouses equipped with newly manufactured HUMITEM air-circulation fans (a circular airflow fan) and Conventional air-circulation fans (a horizontal airflow fan) and to determine the resultant effect of the air-circulation fans on the microclimate using statistical analysis.

2. MATERIALS AND METHODS

2.1 Study area

Sangju Smart Farm Innovation Valley, Sangju-si, Gyeongsangbuk-do (also known as in the North Gyeongsang Province), South Korea, was the experimental site location. Sangju is situated in the south-eastern part of the province, about 20 km southwest of the city of Gumi and about 50 km southeast of the city of Daegu. The city is surrounded by mountains and is situated on the banks of the Nakdong River. Gyeongsangbuk-do is located between the latitudes of 35.4°N and 37.4°N and the longitudes of 128.3°E and 131.4°E and is approximately 60 m above the mean sea level (Park *et al.*, 2011). Gyeongsangbuk-do has a humid subtropical climate with annual mean relative humidity, rainfall, length of day (photoperiod), minimum temperature, and maximum temperature of 73%, 1050 mm, 6.2 hours, -3 °C, and 26°C, respectively. Gyeongsangbuk-do has four seasons: spring (March-May), summer (June-August), fall (September-November), and winter (December-March) (Korea Meteorological Administration, <http://www.kma.go.kr>, accessed on 07 December 2022). Rice, barley, beans, cabbage, strawberries, sesame seeds, garlic, plums, potatoes, tomatoes, apples, cucumber, chestnuts, radish, agaric, and sweet potatoes are among the food crops grown in Gyeongsangbuk-do.

2.2 Experimental setup

This experiment was performed in two tunnel greenhouses and the duration of the experiment was from December 29th 2022 to March 30th, 2023. The rule of thumb recommends that a single-span greenhouse on a latitude above 40°N should have its ridge running east to west to allow low-angle solar rays into the greenhouse from the long sides rather than the ends, while below 40°N latitude the ridge of a single-span greenhouse should be oriented towards north to south since the angle of the sun is higher, was applied. As a result, the orientation of the greenhouses was in the east-west direction, which is the most suitable orientation for SR reception in the study area (Reddy, 2016). The arch-shaped greenhouses were covered with polyolefin and a layer of thermal screen, had the same dimensions of 52.8 m * 6.8 m * 2.5 m (Length × breadth × height) and the same structural configuration (eaves and ridges height of 1.5 m and 2.8 m, respectively Each had a floor area of 18 m² (3 m × 6 m). The thickness and transmittance of the polyethylene film were 200 µm and 91%, correspondingly, while the thickness, conductivity, transmittance, reflectance, and emittances of the thermal screen were 3.5 mm, 0.037 Wm⁻¹ K⁻¹, 0.001, 0.10, and 0.90, correspondingly. Five HUMITEM air-circulation fans (voltage: 220 V; frequency: 60 HZ; allowable fan capacity: 1.16 A; fan maximum speed: 2290 m³/h; power rating: 4.43 hp (3300 W); window-size: 30 cm; wing diameter: 28 cm) were installed in the HUMITEM greenhouse, whereas in the conventional greenhouse (Conv-GH), five conventional air-circulation fans (voltage: 220 V; frequency: 60 HZ; allowable fan capacity: 0.2 A; fan maximum speed: 1500 m³/h; power rating: 0.54 hp (400 W); window-size: 25 cm; wing

diameter: 23 cm) were installed to aid ventilation and distribution of climate variables. The fans in both greenhouses were installed at a distance of 13.2 m from each other. The side vents opened automatically when the greenhouse air temperature was above the set temperature point of 20 degrees Celsius, correspondingly. The optimum air temperature range to enable strawberry development and growth occurs between 18°C to 24°C. Since the experiments were conducted in the winter, a boiler was installed to keep the greenhouses' air space temperature range within the optimum range. The boilers' heating range was 15,000 kcal/h to 62,802 kcal/h, while the heating and continuous hot water supply efficiency were both 90% each. The boilers were set to switch on and start the heating process when the greenhouse air temperature was 9 °C and switched off as soon as the greenhouse air temperature rose to 10 °C.

The *Seolhyang* variety of strawberries was the model crop in the experiments and was transplanted on five 51.2 m long greenhouse benches, that were spaced 1.3 m centre-centre. The strawberry plants were planted in two rows per bed with a centre-centre row spacing of 25 cm apart, resulting in a plant density of 410 per bed and 2050 plants per greenhouse. The same open-loop drip-fertigation system supplied both greenhouses with water and nutrient solution five times daily at an interval of 1 h 30 min, beginning at 08:30, and the duration of each fertigation period was 3 minutes. Standard cultivation practices adopted by Akpenpuun *et al.* (2021) were followed. Figure 1 shows the sensors' location.

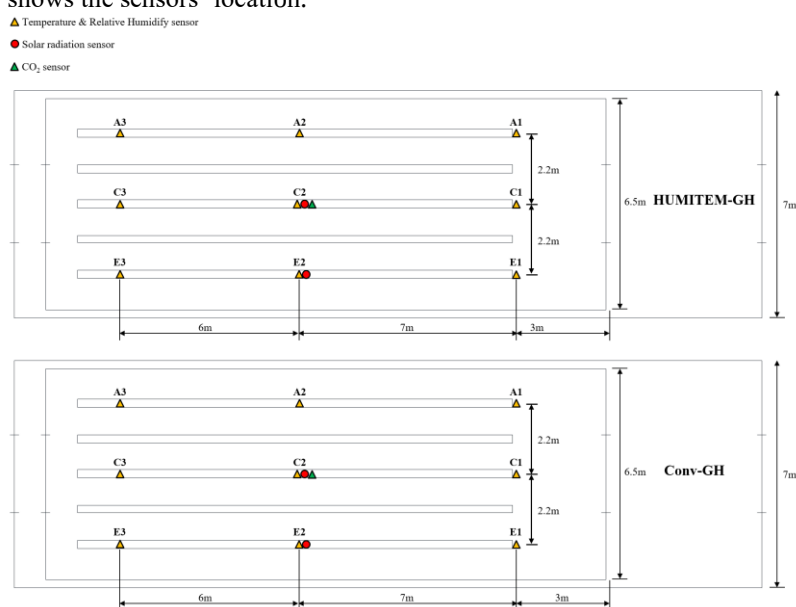


Figure 1. Sensors' location in both GH

2.3 Data collection

The air temperature and relative humidity sensors (temperature: measurement range: -20 °C to 80 °C; accuracy: ± 0.25 °C; humidity: measurement range: 0% to 100% accuracy: $\pm 2\%$, HOBO PRO v2 U23 Pro v2, ONSET, USA) were installed (three per row) at 1.54 m from the floor and placed in protective plastic cases to shield them from direct solar radiation, which could result to inaccuracies in the data. The solar radiation sensors (measurement range: 0 to 1280 W/m²; accuracy: ± 10 W/m² operating temperature range: -40 °C to 70 °C, HOBO RX3000, ONSET, USA) and CO₂ data loggers (Range: 0 to 5,000 ppm; Accuracy: ± 50 ppm $\pm 5\%$ of reading at 25°C (77°F), less than 90% RH; Non-linearity: <1% of FS; Operating Pressure Range: 950 to 1,050 mbar; Sensing Method: Non-dispersive infrared (NDIR) absorption, HOBO MX1102, ONSET, USA) were installed just above the crop canopy. All data loggers recorded readings at ten-minute intervals. The daytime and nighttime data were between the hours of 09:00-16:40 and 16:50-08:50. Total marketable berry fruits were measured (Undeformed fruits and fruits that were 25-30 g and 40-60 mm in diameter). Vapour pressure deficit (VPD) was computed using the method adopted by Abd-El Baky *et al.* (2004).

2.4 Research hypotheses

The hypotheses of a study comparing the climate of two greenhouses might be:

- I. Null Hypothesis (H₀): The null hypothesis (H₀) suggests that there is no significant difference in the climate of the two greenhouses.
- II. Alternative Hypothesis (H₁): The alternative hypothesis (H₁) suggests that there is a significant difference in the climate of the two greenhouses.

2.5 Statistical analysis

To analyze the data collected in the study, descriptive statistics were used to describe the basic features of the data, while the independent samples t-test at $p = 0.01$ or 0.05 levels was used to compare the means of the thermal environments of the two greenhouses. These analyses were carried out using Minitab Statistical software, version 17 (Minitab, LLC, State College, Pennsylvania, USA).

3. RESULTS

The HUMITEM-GH and Conv-GH indoor climates data were recorded for 92 days (29th December 2022-30th March 2023). The daytime climate indices minimum values were 6.24 °C, 39.22%, 0.04 kPa, 0.37 W/m², and 318 ppm for HUMITEM-GH and 5.57 °C, 19.73%, 0.04 kPa, 0.69 W/m², and 355 ppm for Conv-GH. Table 1 presents the comprehensive descriptive statistics of the of the daytime and night-time climate data.

Table 1. Descriptive statistics of both greenhouses' daytime and night-time microclimate indices

Microclimate indices		Temperature, °C	RH, %	VPD, kPa	SR, W/m ²	CO ₂ , ppm
Daytime						
HUMITEM-GH	Mean (±sd)	20.41±4.04	75.63±12.09	0.68±0.42	110.58±84.79	636.9±204.32
	Variance	16.34	146.05	0.18	7189.13	41745.91
	Standard error	0.07	0.22	0.01	1.53	3.69
Conv-GH	Mean (±sd)	17.06±3.95	63.64±19.22	0.78±0.50	157.94±102.76	616.48±139.02
	Variance	15.62	369.58	0.25	10559.55	19327.89
	Standard error	0.07	0.35	0.01	1.86	2.51
Night-time						
HUMITEM-GH	Mean (±sd)	11.10±2.47	90.66±4.00	0.13±0.09		936.26±224.97
	Variance	6.08	16.01	0.01		50609.73
	Standard error	0.03	0.05	0.00		2.97
Conv-GH	Mean (±sd)	10.06±1.74	84.43±6.40	0.19±0.11		730.78±117.81
	Variance	3.03	40.99	0.01		13880.23
	Standard error	0.02	0.08	0.00		1.56

RH = relative humidity; VPD = Vapour pressure deficit; PAR = Photosynthetically active radiation; CO₂ = Carbon dioxide; GH = greenhouse

The T_a distribution ranges of 6 °C-10 °C, 11 °C-15 °C, 16 °C-20 °C, 21 °C-25 °C and 26 °C -30 °C had a frequency of 36, 401, 609, 1786, and 233, respectively, in the HUMITEM-GH, while in the Conv-GH the frequencies were 208, 645, 1433, 768 and 1, respectively. The frequency of the RH distribution ranges of 41%-55%, 56%-70%, 71-85% and 86%-98% in the HUMITEM-GH was 3, 129, 939 and 1994, respectively, and 50, 371, 650, 639 and 1355, respectively, in the Cov._GH. The frequency VPD distribution was 92, 3064 and 1 in the HUMITEM-GH and 119, 3040 and 25 in the Conv-GH for VPD ranges of 0.09 kPa-0.29 kPa, 0.30 kPa-2.00 kPa and >2.00 kPa, respectively.

The analysis of variance (ANOVA) test performed on the daytime data with degrees of freedom of 1 and 6128 gave $F_{\text{statistics}}$, F_{critical} and P_{value} values of 1075.39, 6.64 and <0.01, 854.55, 6.64 and <0.01, 81.47, 6.64 and <0.01, 387.29, 6.64 and <0.01 and 20.93, 6.64 and <0.01, respectively, for T_a , RH, VPD, SR and CO₂. The ANOVA on the night-time data with the degree of freedom of 1 and 11450 gave $F_{\text{statistics}}$, F_{critical} , and P_{value} of 678.17, 6.64 and <0.01, 3896.91, 6.64, <0.01, 1187.87, 6.64 and <0.01 and 3748.96, 6.64 and <0.01, respectively, for T_a , RH, VPD and CO₂. The daytime and night-time comparisons were significantly different at 1% and 5% confidence levels.

The t-test two-sample assuming equal variances result also shows the comparison of the T_a , RH, VPD, SR, and CO₂ were significantly different at P-value less than 1% and 5%, t_{critical} value of 1.96 for daytime data and 2.58 for the night-time data. The t-test result further shows that the comparison between the HUMITEM and conventional greenhouses satisfied the alternative hypothesis that there is a significant difference in the climate of the two greenhouses. This further suggests that the microclimate variables being compared were affected by the type of fan used.

The highest daytime temperature recorded in the HUMITEM-GH and Conv-GH was 25.39 °C and 26.20 °C on 21/02/2023, while the least daytime temperature in the HUMITEM-GH and Conv-GH was 6.24 °C and 5.57 °C, respectively, recorded was on the 24/01/2023. Finally, HUMITEM-GH and Conv-GH T_a were 24.91 °C and 24.69 °C, respectively, on 30/03/2023 the last day of the experiment. The daytime and night-time T_a in the HUMITEM-GH was considerably higher than the T_a in the Conv-GH by 3.35 °C and 1.04 °C.

Likewise, the highest daytime and night-time RH values were 96.27% and 97.20%, and 97.86% and 97.71%, respectively, for HUMITEM-GH and Conv-GH, while the least daytime and night-time RH values were 39.22% and 19.73%, and 46.28% and 20.76%, respectively, for HUMITEM-GH and Conv-GH. Most of the time during the day, RH in the HUMITEM-GH was higher than RH in the Conv-GH because the HUMITEM circulation fans were able to move a greater volume of air around the greenhouse than the conventional air circulation fans. The difference between the least RH in the HUMITEM-GH and Conv-GH was 19.49% in the daytime and 25.52% in the night-time. Even though HUMITEM-GH and Conv GH both had slightly higher RH levels, the differences between the two were not particularly noteworthy.

The HUMITEM-GH and Conv-GH had respective mean daytime VPD of 0.68 ± 0.42 kPa and 0.78 ± 0.50 . In the HUMITEM-GH and Conv GH, respectively, the maximum values of VPD during the daytime were 2.07 kPa and 2.25 kPa. The HUMITEM-GH mean daytime VPD was slightly lower than Conv-GH VPD. The night-time VPD mean was 0.13 ± 0.09 kPa and 0.19 ± 0.11 kPa in the HUMITEM-GH and Conv-GH, respectively. VPD in the Conv-GH was higher than HUMITEM-GH most of the time during the day and followed the same trend as RH. Although slightly higher VPD was observed in the Conv-GH than in the HUMITEM-GH, the overall difference was statistically insignificant. However, both greenhouses had roughly the same mean night-time VPD and a similar pattern of variation.

The daytime CO₂ range in the HUMITEM-GH, Conv GH, and outdoor was 318.0-2083 ppm and 355.0-1514 ppm, respectively. The night-time CO₂ range in the HUMITEM-GH and Conv GH was 344-2669 ppm and 356-1081 ppm. According to the descriptive statistics, the mean daytime CO₂ in the HUMITEM-GH and Conv-GH were, respectively, 636.90 ± 204.32 ppm and 616.48 ± 139.02 ppm. The night-time CO₂ mean was also 936.26 ± 224.97 ppm and 730.78 ± 117.81 ppm, respectively, in the HUMITEM-GH, Conv GH, and outdoor. The result of the analysis of variance showed that the CO₂ levels in both greenhouses were statistically significant at a 99% level of confidence (df1 = 1, df2 = 6128). Also, the t-Test showed that the CO₂ levels were statistically significant.

Since both greenhouses had the same orientation, structural layout, covering material, and dimensions from the start, the SR of the HUMITEM-GH and the Conv-GH had the same pattern, but the differences were statistically insignificant.

The total yield in the HUMITEM-GH and Conv-GH was 444.51 kg and 328.18 kg, respectively, making the yield in the HUMITEM-GH higher than the Conv-GH by 116.33 kg. The marketable yield was 388.05 kg and 290.36 kg, respectively, for the HUMITEM-GH and Conv-GH. The mean marketable yield was 6.93 ± 4.28 kg and 5.19 ± 3.72 kg in the HUMITEM-GH and Conv-GH, in that order. The total and marketable yields in the HUMITEM-GH were statistically significant from the Conv-GH at the confidence level of 95%.

4. DISCUSSION

The daytime T_a recorded in the HUMITEM-GH and Conv-GH was in the range of 6.24 °C-26.81 °C and 5.57 °C-26.20 °C, correspondingly, while the night-time T_a was 6.07 °C-23.77 °C and 5.57 °C-20.84 °C, respectively for the HUMITEM-GH and Conv-GH. Pearce *et al.* (1993) reported that temperatures between 10 °C and 30 °C positively impact the growth rates of fruit in a closed environment. Balendonck *et al.* (2010) experimented with measuring the extent of climate unevenness and determining the number of sensing points for precise estimation of the spatial and temporal climate variable distribution in four commercial greenhouses observed averaged spatial differences of 1.0 °C - 3.4 °C for temperature, whereas in this experiment average spatial differences were 0.26 °C-5.24 °C and 0.65 °C-5.69 °C in the HUMITEM-GH and Conv-GH. During this research, the maximum daytime and night-time temperature difference between HUMITEM-GH and Conv-GH were found to be 0.60 °C and 2.94 °C with the HUMITEM-GH having higher temperatures than the Conv-GH. Sim *et al.* (2020) reported day- and night-time temperatures in the range of 15°C-25°C and 5°C-10°C, correspondingly, in an air-inflated and conventional double-layer greenhouse. It was observed that just as spring began in March, the mean temperatures in both greenhouses increased by 0.55 °C and 1.46 °C, respectively, in the HUMITEM-GH and Conv-GH. This increase in greenhouse air temperature could be explained by a greater number of sunny days and photoperiod per day as a result of higher solar radiation intensity compared to winter.

The RH recorded in the HUMITEM-GH and Conv-GH was in the range of 40.22%-97.20% and 19.73%-97.79%, and 46.28%-97.86% and 20.76%-97.75%, correspondingly, for daytime and night-time. Jayasekara *et al.* (2018) reported 85% in a double-layer greenhouse that was heavily saturated at night, however, during the daytime, RH was as low as 40%. Kroggel and Kubota (2017) recommended a maximum night-time RH of 95% and an optimum daytime humidity in the range of 40%–60% to avoid tip burn. Only the HUMITEM-GH had its RH within the recommended ranges. The change in weather from winter to spring which caused an increase in temperature

resulted in increased plant growth and physiological activity including evaporation and consequent increase in the RH by 6.22% and 8.04% in the HUMITEM-GH and Conv-GH, respectively.

The VPD recorded in the HUMITEM-GH and Conv-GH was in the range of 0.04 kPa to 2.07 kPa and 0.03 kPa to 2.25 kPa, and 0.03 kPa -1.57 kPa and 0.03 kPa -1.73 kPa, correspondingly, in the day and night. The difference between the outdoor VPD and that inside the HUMITEM-GH was 0.18 kPa. Amani *et al.* (2020) and Wollaeger and Runkle (2017) recommended ranges of 0.3 to 1.3 kPa and 0.8 to 1.0 kPa, correspondingly. Although the lower limit of VPD recorded in both greenhouses was lower than the recommended 0.5 kPa, the frequency of the VPD values that were within the recommended range of 0.3 to 2.0 kPa was 2921 and 2972 for the HUMITEM-GH and Conv-GH, respectively. The VPD in both greenhouses was significantly different with the HUMITEM-GH having higher VPD values that are within the recommended range that the Conv-GH.

The CO₂ recorded in the HUMITEM-GH and Conv-GH greenhouse was in the range of 318 $\mu\text{mol}\cdot\text{mol}^{-1}$ -2083 $\mu\text{mol}\cdot\text{mol}^{-1}$ and 355 $\mu\text{mol}\cdot\text{mol}^{-1}$ 1514 v $\mu\text{mol}\cdot\text{mol}^{-1}$, correspondingly. There is evidence that CO₂ concentrations in the range of 800 $\mu\text{mol}\cdot\text{mol}^{-1}$ and 1500 $\mu\text{mol}\cdot\text{mol}^{-1}$ can considerably improve growth, while exposure to a CO₂ concentration of less than 350 ppm, the outdoor CO₂ concentration indoors, could be detrimental to growth (Kim *et al.*, 2022). The mean daytime and night-time CO₂ concentration in the HUMITEM-GH was higher than the concentration in the Conv-GH and there was a significant difference between the two greenhouses. However, the CO₂ concentration in the HUMITEM-GH was still in the ranges of 340-1000 $\mu\text{mol}\cdot\text{mol}^{-1}$, 800-1000 $\mu\text{mol}\cdot\text{mol}^{-1}$, 1000 -1500 $\mu\text{mol}\cdot\text{mol}^{-1}$ and 900-1000 ppm recommended by Garcia and Kubota (2017), and Durkin (1992), correspondingly. The lower CO₂ concentration recorded in HUMITEM-GH can be attributed to the operation of the HUMITEM fans which had a higher capacity for circulation and increased ventilation rates.

The SR recorded in the HUMITEM-GH and Conv-GH was in the range of 0.37 W/m²-520.74 W/m² and 0.69 W/m²-448.68 W/m², correspondingly. These SR ranges are similar to the SR range of 8.7 W/m² -549.8 W/m² and 3.2 W/m²-631.6 W/m² recorded by Akpenpuun *et al.* (2021) in single-layer and double-layer greenhouses. The SR in both greenhouses was nearly the same as there was no significant difference between the amount of radiation received by each greenhouse. This might be because both greenhouses were side by side and structurally the same and the fans had no interference with SR reception. The HUMITEM-GH and Conv-GH receive more solar irradiance (20 W/m² over 10 hours) in March when the sun was more southerly compared to November to February (9 W/m² over 8 hours) when the sun was more easterly.

5. CONCLUSIONS

The finding from the research highlights the importance of selecting the appropriate air-circulating fan to improve the microclimate of a naturally ventilated greenhouse. The study found that by using HUMITEM air-circulating fans, the distribution of climate variables was significantly improved, resulting in a near-optimal growing condition. The significant difference between the Conv-GH and HUMITEM-GH yield can be attributed to the significant difference between the Conv-GH and HUMITEM-GH microclimates. The use of HUMITEM air-circulating fans could have a significant impact on the commercial production of plants, providing farmers and horticulturists with a tool to optimize the growing conditions of their crops. The improved distribution of climate variables can increase the efficiency of the greenhouse environment, thereby, resulting in higher yield, reduced energy consumption, and consequently resulting in cost savings for growers.

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