

COMPARATIVE ANALYSIS OF THE MICRO-ENVIRONMENTS OF SINGLE-SPAN TRIPLE-LAYERED GREENHOUSES UNDER DIFFERENT AIRFLOW SYSTEMS

Timothy Denen Akpenpuun¹, Qazeem Opeyemi Ogunlowo^{2,6}, Wook-Ho Na³, Anis Rabi², Misbaudeen Aderemi Adesanya², Prabhat Dutta⁴, Ezatullah Zakir⁴, Oluwasegun Moses Ogundele⁵, Hyun-Woo Lee^{2,3*}

¹Department of Agricultural, and Biosystems Engineering,
University of Ilorin, PMB 1515, Ilorin 240003, Nigeria;

²Department of Agricultural Civil Engineering, College of Agricultural and Life Sciences,
Kyungpook National University, Daegu 41566, Korea;

³Smart Agriculture Innovation Centre, Kyungpook National University, Daegu 41566, Korea;

⁴Department of Food Security and Agriculture Development

⁵ International Institute for Tropical Agriculture Ibadan (IITA), Ibadan, Nigeria.

⁶ Department of Agricultural, and Bioenvironmental Engineering,

Federal College of Agriculture, Moor Plantation, PMB 5029, Ibadan, Nigeria

*Corresponding Author's Email: whlee@knu.ac.kr & akpenpuun.td@unilorin.edu.ng;

Tel.: +82-53-950-5736

ABSTRACT

The microclimate within indoor production systems is intricately linked to the macroclimate of their surrounding environment, resulting in dynamic fluctuations over time. This study investigated the variations in thermal conditions within two adjacent single-span tunnel greenhouses, each utilizing distinct airflow systems: one equipped with circular airflow fans (HUMITEM-GH) and the other with horizontal airflow fans (Conv-GH). Temperature (Ta), relative humidity (RH), vapor pressure difference (VPD), solar radiation (SR), and carbon dioxide (CO₂) levels were monitored using standard methods, and data analysis was conducted using MINITAB software. Statistical analysis included descriptive statistics, analysis of variance (ANOVA), and t-tests. The results of the experiment showed that in the HUMITEM-GH and Conv-GH, the minimum daytime Ta, RH, VPD, SR, and CO₂ were 6.24°C, 39.22%, 0.04 kPa, 0.37 W/m², and 318 ppm, and 5.57°C, 19.73%, 0.03 kPa, 0.69 W/m², and 355 ppm, respectively. Whereas the maximum daytime Ta, RH, VPD, SR, and CO₂ were 26.81°C, 97.20%, 2.07 kPa, 520.74 W/m², and 2083 ppm, and 26.20°C, 97.79%, 2.25 kPa, 448.68 W/m², and 1514 ppm, respectively. In the same context, climate parameters at night ranged from 6.07°C to 23.77°C, 46.28% to 97.86%, 0.03 kPa to 1.57 kPa, and 344 ppm to 2669 ppm, respectively, for the HUMITEM-GH, and from 5.57°C to 20.84°C, 20.76% to 97.75%, 0.03 kPa to 1.73 kPa, and 356 ppm to 1081 ppm, respectively, for the Conv-GH. There were significant differences between the two greenhouses both in the daytime and nighttime, with the HUMITEM-GH having higher and near-optimal climate parameters than the Conv-GH. These results have shown that the newly developed HUMITEM air circulation fan has superior air circulation and flow capabilities compared to conventional air circulation fans. This information may be of interest to farmers, horticulturists, and researchers involved in protected crop/plant production, offering valuable guidance for optimizing greenhouse environments.

Keyword: HUMITEM, Air-circulation; Distribution; Monitor; Horizontal airflow

1. INTRODUCTION

A greenhouse is an indoor cropping system that allows the manipulation and control of environmental, nutrition, and biological variables (Amitrano *et al.*, 2021). 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 (Ghoulem *et al.*, 2019). 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; Akpenpuun *et al.*, 2023). 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 (Ghani *et al.*, 2019). 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; Akpenpuun *et al.*, 2022). 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; Akpenpuun and Mijinyawa, 2018).

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; Ogunlowo *et al.*, 2021).

In the greenhouse, airflow is restricted by the structural members, plants, and equipment, resulting in a sharp increase in indoor temperature (Bailey *et al.*, 2003). Therefore, knowing the behaviour of meteorological elements, such as temperature, RH, VPD, SR, and CO_2 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 CO_2 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 (Narimani *et al.*, 2021). Regular monitoring and adjustments to the greenhouse environment would help ensure the optimal growth and productivity of plants (Montoya, *et al.*, 2020; Li *et al.*, 2023).

The objectives of this study were to analyze and compare changes in the thermal environment of two tunnel greenhouses equipped with newly developed 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

The experimental site for this study was located in Sangju Smart Farm Innovation Valley, situated in Sangju-si, Gyeongsangbuk-do, South Korea, also known as North Gyeongsang Province. Sangju is positioned in the southeastern part of the province, approximately 20 km southwest of Gumi and 50 km southeast of Daegu. Nestled amidst mountains, Sangju is bordered by the Nakdong River. Gyeongsangbuk-do spans between latitudes 35.4°N and 37.4°N, and longitudes 128.3°E and 131.4°E, with an elevation of approximately 60 meters above mean sea level (Park *et al.*, 2011).

Characterized by a humid subtropical climate, Gyeongsangbuk-do experiences an annual mean relative humidity of 73%, rainfall of 1050 mm, photoperiod of 6.2 hours, minimum temperature of -3 degrees Celsius, and maximum temperature of 26 degrees Celsius. The region observes four distinct 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).

A diverse array of food crops thrives in Gyeongsangbuk-do, including rice, barley, beans, cabbage, strawberries, sesame seeds, garlic, plums, potatoes, tomatoes, apples, cucumber, chestnuts, radish, agaric, and sweet potatoes.

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 applied 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. As a result, the orientation of the greenhouses was in the east-west direction, which is the most suitable orientation for solar radiation (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. Four 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); RPM: window-size: 30 cm; wing diameter: 28 cm) were installed in the HUMITEM greenhouse, whereas in the conventional greenhouse (Conv-GH), four 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); RPM: 1650; window-size: 25 cm; wing diameter: 23 cm; HUMITEM, Sangju-si, Korea) 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 ranges 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 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 environmental variables measured in both greenhouses were solar radiation (SR, W/m²), relative humidity (RH, %), carbon dioxide (CO₂, ppm), and air temperature (T_a, °C), and these parameters were measured using their respective sensors and data loggers.

The experimental crop was the *Seolhyang* variety of strawberries, which were cultivated on five greenhouse benches, each measuring 51.2 meters in length and spaced 1.3 meters apart. Within each bench, the strawberries were arranged in two rows with a centre-to-centre spacing of 25 centimetres, resulting in a plant density of 410 per bench and 2050 plants per greenhouse. A uniform open-loop drip-fertigation system was utilized to supply water and nutrient solution to both greenhouses, with five daily applications at 1.5-hour intervals starting at 08:30. Each fertigation session lasted 3 minutes, following the standard cultivation practices outlined by Akpenpuun et al. (2021). Figure 1 depicts the location of the sensors used in the study.

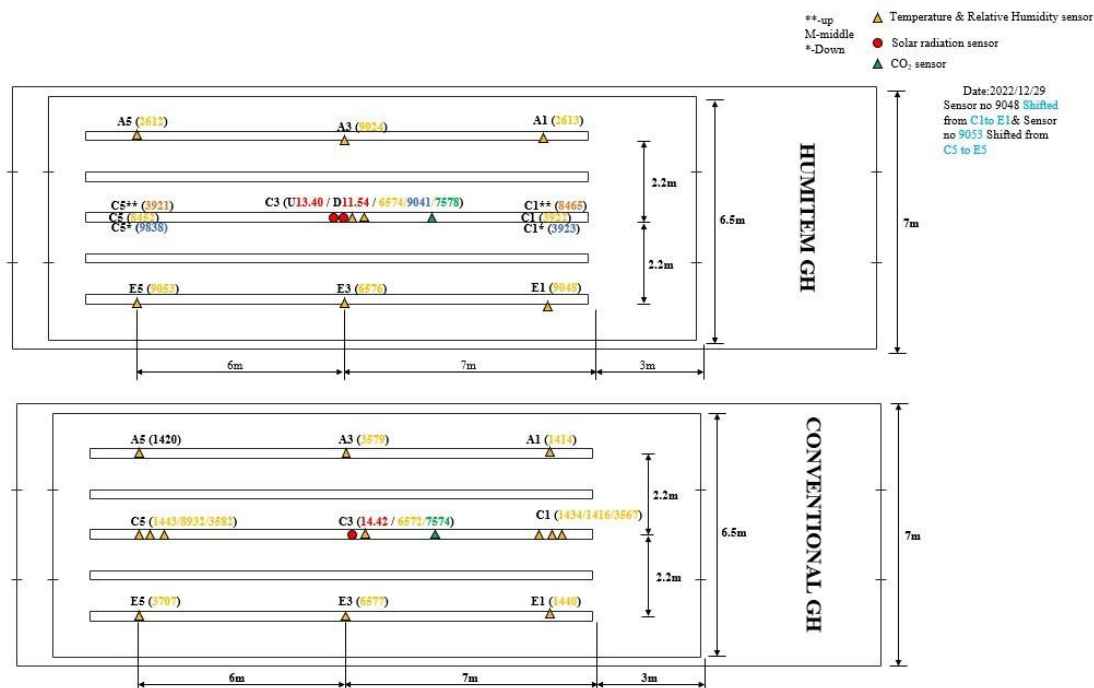


Figure 1. Sensors' location in both Greenhouses

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) were installed just above the crop canopy. All data loggers recorded readings at ten-minute intervals. The daytime and night time were between the hours of 0900-1640 and 1650-0850 and were recorded for 92 days (29th December 2022-30th March 2023). Only marketable berry fruits were measured (Undeformed fruits and fruits that are 25-30 g and 40-60 cm in diameter). Vapor pressure deficit (VPD) was computed using the following formulas (Abd-El Baky *et al.*, 2004).

$$VP_{sat} = \exp(Z) \quad (1)$$

$$Z = \frac{A}{T} + B + C(T) + DT^2 + ET^3 + F \ln T \quad (2)$$

$$VP_{air} = \frac{VP_{sat} \times RH}{100} \quad (3)$$

$$VPD = (VP_{sat} - VP_{air}) \frac{145}{1000} \quad (4)$$

where:

$$A = -1.04 \times 10^{-4};$$

$$B = -1.13 \times 10^{-1};$$

$$C = -2.70 \times 10^{-2};$$

$$D = +1.29 \times 10^{-5};$$

$$E = -2.48 \times 10^{-9}; \text{ and}$$

$$F = + 6.55$$

T = air temperature in °R; RH = air relative humidity (%) of the greenhouse.

VP_{sat} = air saturation vapor pressure (psi);

VP_{air} = vapor pressure of the air (psi); and

VPD = vapor pressure deficit (kPa)

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 0.005 levels was used to compare the means of the thermal environments of the two greenhouses. All the statistical analyses were carried out using Minitab Statistical software, version 17 (Minitab, LLC, State College, Pennsylvania, USA).

3. RESULTS

The data was segregated into daytime and night time. The daytime and night time data were collected between 0900 to 1640 and 1650 to 0850, respectively. Presented in Table 1 is the descriptive statistics of the daytime and night time climate indices.

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
	Skewness	-0.93	-0.28	0.50	1.48	1.84
	Kurtosis	0.00	-0.70	-0.47	2.25	5.09
	Min	6.24	39.22	0.04	0.37	318
	Max	26.81	97.20	2.07	520.74	2083
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
	Skewness	-0.43	-0.23	0.43	0.41	1.25
	Kurtosis	-0.66	-1.02	-0.71	-0.52	3.09
	Min	5.57	19.73	0.03	0.69	355
	Max	26.20	97.79	2.25	448.68	1514
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
	Skewness	1.06	-2.59	6.66		0.56
	Kurtosis	2.00	19.00	71.89		2.69
	Min	6.07	46.28	0.03		344
	Max	23.77	97.86	1.57		2669
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
	Skewness	2.45	-1.68	5.90		0.28
	Kurtosis	7.76	12.62	59.11		0.31
	Min	5.57	20.76	0.03		356
	Max	20.84	97.75	1.73		1081

where:

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

For the daytime data of the HUMITEM-GH, the temperature distribution reflects adherence to the recommended range of 11 °C to 30°C, with varying frequencies across different temperature bands. Notably, the highest frequency occurs within the 21°C to 25°C range, indicating prevalent conditions within this temperature bracket. This suggests that the HUMITEM-GH generally maintains temperatures conducive to plant growth and development during the daytime. Both greenhouses were observed to maintain nighttime temperatures within the recommended range of 11 to 30°C, although there were variations in the frequency distribution within specific temperature bands. However, the HUMITEM-GH tends to exhibit slightly higher frequencies within this range compared to the Conv.-GH, suggesting potentially more consistent temperature control during the night.

In terms of relative humidity (RH), the distribution largely falls within the recommended range of 41 to 85%, although instances of exceeding the upper limit are noted. The frequency distribution reveals that RH levels between 76% to 85% are most prevalent, indicating moderate to high humidity levels during the daytime. This suggests that while RH levels in the HUMITEM-GH are generally within the recommended range, there may be occasional periods of higher humidity. Similarly, the RH in both greenhouses maintained nighttime RH levels within the recommended range of 41 to 85%. However, there were instances where the RH exceeds the upper limit in both setups. The HUMITEM-GH shows a higher frequency of RH levels within the recommended range compared to the Conv.-GH during the night, indicating potentially better RH management in the former.

Similarly, the vapor pressure deficit (VPD) distribution was within the recommended range of 0.4 to 2.00 kPa, with frequencies distributed across different VPD ranges. The highest frequency is observed within the 0.3-0.7 kPa range, indicating relatively favourable VPD conditions. This suggests that the HUMITEM-GH maintained VPD levels within the recommended range during the daytime, contributing to favourable microclimate conditions for plant growth and development. In the night time, however, both greenhouses showed VPD levels spanning from 0.09 to 2.20 kPa, with the recommended range being 0.4 to 2.00 kPa. While both setups achieved the recommended range, there were variations in frequency distribution within specific VPD ranges. The HUMITEM-GH demonstrates a more consistent distribution within the recommended VPD range compared to the Conv.-GH during the night, suggesting potentially more effective VPD management in the HUMITEM-GH. Tables 2 and 3 presents the daytime and night time frequency distribution of indoor parameters in both greenhouses. This frequency distribution shows the ranges of all the parameters making it easy to identify the ranges that are within the optimum required for indoor cropping.

Table 2. Daytime frequency distribution of indoor parameters in the HUMITEM-GH and Conv.-GH

HUMITEM-GH								
S/No.	Temp. Range Frequency		RH Range Frequency		VPD Range Frequency		SR Range Frequency	
1	6-10	36	26-40	0	<0.09	53	<40	502
2	11-15	401	41-55	3	0.1-0.29	39	40-90	1145
3	16-20	609	56-70	129	0.3-0.7	684	90-140	588
4	21-25	1786	76-85	939	0.7-1	889	141-190	367
5	26-30	233	86-97.20	1994	1-1.3	710	191-240	198
6					1.3-1.6	418	241-290	101
7					1.6-1.9	203	291-340	79
8					2.00	61	341-390	53
9					2.01-2.53	7	391-540	32
CONV.-GH								
S/No.	Temp. Range Frequency		RH Range Frequency		VPD Range Frequency		SR Range Frequency	
1	6-10	208	26-40	50	<0.09	104	<40	445
2	11-15	645	41-55	371	0.1-0.29	15	40-90	385
3	16-20	1433	56-70	650	0.3-0.70	579	90-140	649
4	21-25	768	76-85	639	0.7-1.0	378	141-190	508
5	26-30	11	86-97.79	1355	1.0-1.30	975	191-240	376
6					1.30-1.60	483	241-290	316
7					1.60-1.90	335	291-340	234
8					2.00	149	341-390	96
9					2.20-2.53	22	391-540	56

The analysis of variance (ANOVA) test, shown in Table 4, performed on the daytime and night time showed that the HUMITEM-GH and Conv.-GH daytime and night time comparisons were significantly different at 1% confidence levels.

The t-test two-sample assuming equal variances result in Table 5 shows the comparison of the means of Ta, RH, VPD, SR, and CO₂. The t-test result shows that the comparison between the HUMITEM and conventional greenhouses satisfied the alternative hypothesis, that there is a statistically significant difference between the means of the two environments. This result suggests that there are strong evidences that support the hypothesis that the microclimate variables being compared were affected by the type of fan used.

Table 3. Night time frequency distribution of indoor parameters in the HUMITEM-GH and Conv.-GH

HUMITEM-GH						
S/No.	Temp. Range Frequency		RH Range Frequency		VPD Range Frequency	
1	<5	0.00	<25	0	<0.09	1653
2	6-10	2186	26-40	0	0.1-0.29	444
3	11-15	3192	41-55	0	0.3-0.70	3469
4	16-20	310	56-70	7	0.7-1.0	101
5	21-25	38	76-85	17	1.0-1.30	49
6	26-30	0	86-100	5702	1.30-1.60	4
7					1.60-1.90	6
CONV.-GH						
S/No.	Temp. Range Frequency		RH Range Frequency		VPD Range Frequency	
1	<5	0.00	<25	0	<0.09	474
2	6-10	3902	26-40	3	0.1-0.40	56
3	11-15	1664	41-55	8	0.4-0.70	5098
4	16-20	156	56-70	15	0.7-1.0	53
5	21-25	4	76-85	34	1.0-1.30	20
6	26-30	0	86-100	5666	1.30-1.60	12
7					1.60-2.00	10
8					2.01-0.2.20	3

The highest daytime temperatures recorded in both the HUMITEM-GH and Conv-GH were 26.81 °C and 26.20 °C, respectively, on 21/02/2023. Conversely, the lowest daytime temperatures in the HUMITEM-GH and Conv-GH on 24/01/2023 were 6.24 °C and 5.57 °C, respectively. Additionally, on the last day of the experiment, 30/03/2023, the recorded temperatures for HUMITEM-GH and Conv-GH were 24.91 °C and 24.69 °C, respectively. Notably, throughout the experiment, it was observed that the temperature in the HUMITEM-GH consistently exceeded that of the Conv-GH, with differences of 3.35 °C and 1.04 °C, respectively, in the daytime and nighttime periods.

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 lowest 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 and more evenly distributed than RH in the Conv-GH because the HUMITEM circulation fans were able to move a larger volume of air around the greenhouse and outside than the conventional air circulation fans. The difference between the lowest RH in the HUMITEM-GH and Conv-GH was 19.49% in the daytime and 25.52% in the night time.

Table 4. ANOVA result of HUMITEM-GH vs Conv-GH data

Daytime					
S/No.	Groups	F	P-value	F crit	DF
1	C-Temp/H-Temp	1075.39	1.88E-217	6.64	1/6128
2	C-RH/H-RH	854.55	5.62E-176		
3	C-VPD/H-VPD	81.47	2.34E-19		
4	C-SR/H-SR	387.29	1.18E-83		
	C-CO ₂ /H-CO ₂	20.93	4.86E-06		
Night time					
S/No.	Groups	F	P-value	F crit	DF
	C-Temp/H-Temp	678.17	2.71E-145	6.637	1/11450
2	C-RH/H-RH	3896.91	0.00		
3	C-VPD/H-VPD	1187.87	9.20E-248		
4	C-CO ₂ /H-CO ₂	3748.96	0.00		

where:

C-Temp,

H-Temp,

C-RH,

H-RH,

C-VPD,

H-VPD,

C-SR, and

H-SR, C-CO₂, H-CO₂ = conventional/ HUMITEM greenhouse temperature, relative humidity, vapour pressure deficit, solar radiation, carbon dioxide.

The HUMITEM-GH and Conv-GH had respective mean daytime VPD was 0.68 ± 0.42 kPa and 0.78 ± 0.50 . Similarly, the maximum values of VPD in the daytime was 2.07 kPa in the HUMITEM-GH and 2.25 kPa in the Conv-GH. 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. The percentage of VOD values within the recommended range of 0.3 kPa to 2.00 kPa for optimum indoor cropping was 96.97% in the HUMITEM-GH and 95.30% in the Conv-GH. This shows that both greenhouses were similar in VPD values.

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.

Table 5. t-Test of HUMITEM and Conventional greenhouses

Time	Statistics	T _{aH} /T _{aC}	RH _H /RH C	VPD _H /VPD C	SR _H /SR C	CO _{2H} /CO ₂ C
Daytime	Pooled Variance	15.98	257.81	0.22	8874.34	30536.9
	Degree of freedom	6128	6128	6128	6128	6128
	t Statistics	-32.79	-29.23	9.03	19.68	-4.57
	P(T<=t) one-tail	9.38E-218	2.81E-176	1.17E-19	5.90E-84	2.43E-06
	t Critical one-tail	1.65	1.65	1.65	1.65	1.65
	P(T<=t) two-tail	1.88E-217	5.62E-176	2.34E-19	1.18E-83	4.86E-06
	t Critical two-tail	1.96	1.96	1.96	1.96	1.96
Time	Statistics	T _{aH} /T _{aC}	RH _H /RH C	VPD _H /VPD C	SR _H /SR C	CO _{2H} /CO ₂ C
Night time	Pooled Variance	4.56	28.50	0.01		32244.98
	Degree of freedom	11450	11450	11450		11450
	t Statistics	-26.04	-62.43	34.47		-61.23
	P(T<=t) one-tail	1.35E-145	0.00	4.60E-248		0.00
	t Critical one-tail	2.33	2.33	2.33		2.33
	P(T<=t) two-tail	2.71E-145	0.00	9.2E-248		0.00
	t Critical two-tail	2.58	2.58	2.58		2.58

In the HUMITEM-GH and Conv GH the mean SR was, respectively, $110.58 \pm 84.79 \text{ Wm}^{-2}$ and $157.94 \pm 2.76 \text{ Wm}^{-2}$. With the maximum value for SR of 529.74 Wm^{-2} and 448.68 Wm^{-2} was recorded in the HUMITEM-GH, Conv GH, respectively. Despite the fact that both greenhouses had the same orientation, structural layout, covering material, and dimensions, the SR received by the HUMITEM-GH and Conv-GH were significant different. However, the SR received by both greenhouses was sufficient to support the test crop.

The total yield was 445 kg and 328 kg, while the total marketable yield was 388 kg and 290 kg, respectively in the HUMITEM-GH and Conv-GH. The HUMITEM-GH ability to create the near ideal climate conditions needed for strawberry optimum production can be used to explain the difference in yield. Figure 1 displays the total output and total marketable yields harvested in both greenhouses. For both greenhouses, the harvested yield had an oscillating pattern with each big harvest followed by a smaller harvest (Figure 2).

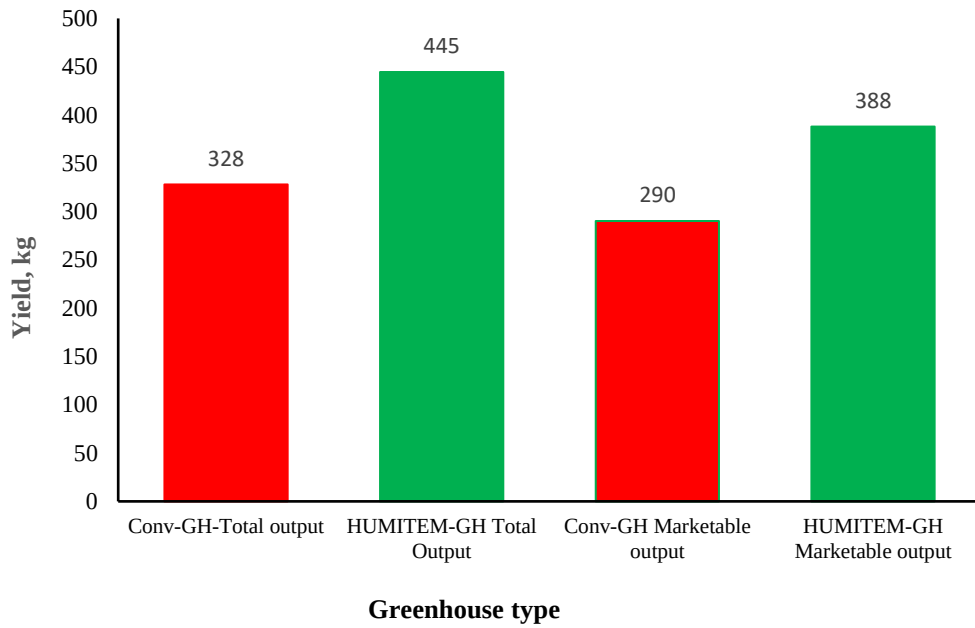


Figure 1. The total output and total marketable yields

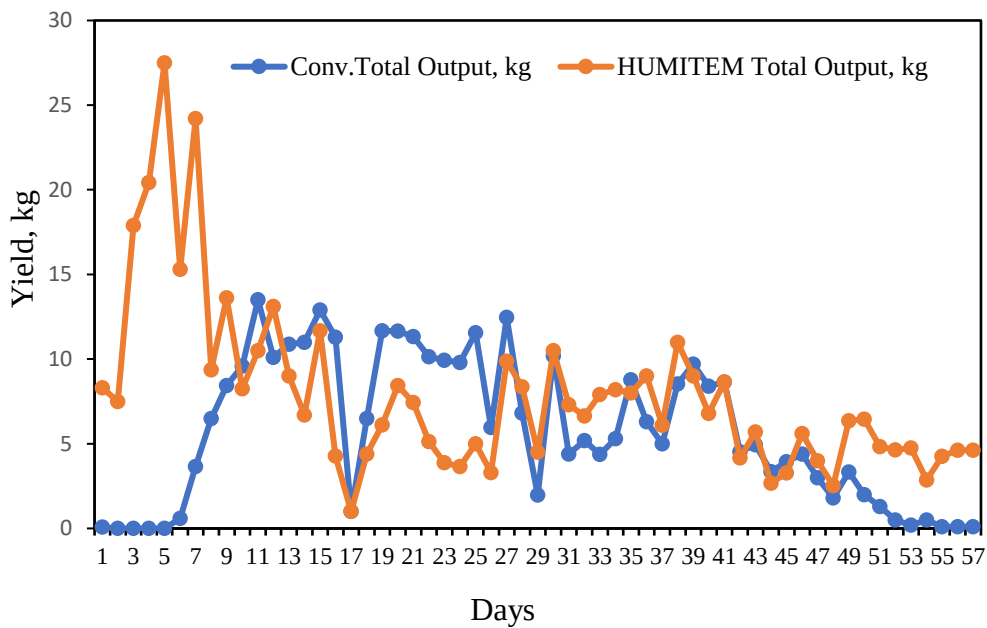


Figure 2. Yield trend

The analysis of variance carried out on the total output and total marketable yields show that the yields in the greenhouses were significantly different as shown in Table 6.

Table 6. ANOVA of total output and total marketable yield

Groups	df	F	P-value	F crit
Marketable Conv-GH yield/HUMITEM yield	1/110	5.29	0.02	3.93
Total Conv yield/HUMITEM yield	1/110	5.45	0.02	3.93

4. DISCUSSION

The daytime T_a recorded in the HUMITEM-GH and Conv-GH was in the range of 6.24 °C to 26.81 °C and 5.57 °C to 26.20 °C, correspondingly, while the night time T_a was 6.07 °C to 23.77 °C and 5.57 °C to 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 to 3.4 °C for temperature, whereas in this experiment average spatial differences were 0.26 °C to 5.24 °C and 0.65 °C to 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 to 25 °C and 5 °C to 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% to 97.20% and 19.73% to 97.79%, and 46.28% to 97.86% and 20.76% to 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% to 60% to avoid tip burn. According to ASABE (2015) standards, RH levels in the 60 to 90 per cent range are ideal for greenhouse vegetables. 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 to 1.57 kPa and 0.03 kPa to 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. Shamshiri and Ismail (2013) Amani *et al.* (2020) and 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 than 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 to 1000 $\mu\text{mol}\cdot\text{mol}^{-1}$, 800 to 1000 $\mu\text{mol}\cdot\text{mol}^{-1}$, 1000 to 1500 $\mu\text{mol}\cdot\text{mol}^{-1}$ and 900-1000 ppm recommended by Blom *et al.* (2002), Kläring *et al.* (2007), 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 to 520.74 W/m² and 0.69 W/m² to 448.68 W/m², correspondingly. These SR ranges are similar to the SR range of 8.7 W/m² to 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 minimum SR recommended by Hidaka *et al.* (2013) for indoor cropping is in the ranges of 45.4 Wm⁻² to 71.9 Wm⁻² and 75.7 Wm⁻² to 95.6 Wm⁻². Faust *et al.* (2005), on the other hand, recommended SR in the range of 18.9 Wm⁻² to 37.9 Wm⁻² for low light greenhouse crops, 37.9 Wm⁻² to 75.7 Wm⁻² for medium light greenhouse crops, 75.7 Wm⁻² to 113.5 Wm⁻² and >113.5 Wm⁻² for high light and very high light greenhouse crops. Based on the mean value of SR in the HUMITEM-GH, the HUMITEM-GH was in the range of light for low light greenhouse crops, while the SR in the Conv-GH was in the high light and very high light greenhouse crops band.

The mean total yield on a harvest day was 7.94±26.14 kg and 5.86±18.22 kg, respectively, in the HUMITEM-GH and Conv-GH. Similarly, the mean marketable yield on a harvest day was 6.93±18.32 kg in the HUMITEM-GH and 5.19±13.87 kg in the Conv-GH. The mean marketable yield per plant per harvest day was 0.22 kg in the HUMITEM-GH and 0.16 kg in the Conv-GH. The differences in both total output and total marketable yield indicate that the HUMITEM-GH provided a better microclimate compared to the Conv-GH.

5. CONCLUSIONS

The research findings underscore the critical role of selecting suitable air-circulating fans to improve the uniform distribution of microclimate factors within naturally ventilated greenhouses, as these parameters, significantly influence plant development, growth, and yield. The adoption of HUMITEM air-circulating fans holds considerable potential for enhancing commercial greenhouse crop production as the HUMITEM air-circulating fans significantly improved the distribution of climate variables, leading to near-optimal growing conditions. These fans offer farmers and horticulturists a means to fine tune growing conditions, thereby optimizing crop performance. The enhanced distribution of climate variables not only impacts overall greenhouse efficiency but also reduces energy consumption, translating into cost savings for growers. In conclusion, while both greenhouses generally maintain conditions within the recommended parameters during the daytime and night time, the HUMITEM-GH shows slightly more consistent temperature, RH, and VPD distributions compared to the Conv.-GH. These differences may indicate more effective climate control mechanisms in the HUMITEM-GH, potentially resulting in better overall microclimate conditions for plant growth, development and yield.

AUTHOR CONTRIBUTIONS

Conceptualisation, T.D.A, H.W.L., W.H.N., and H.T.K.; methodology, T.D.A., W.H.N., Q.O.O., and P.D.; formal analysis, T.D.A.; investigation, T.D.A, W.H.N., Q.O.O., P.D., A.R., M.A.A. E.Z., and O.S.T.; resources, H.W.L.; data curation, T.D.A., and W.H.N.; writing—original draft preparation, T.D.A.; writing—review and editing, T.D.A., O.S.T., M.O.S., H.T.K. and H.W.L.; visualisation, T.D.A., and W.H.N.; supervision, H.W.L., and H.T.K.; project administration, H.W.L.; funding acquisition, H.W.L. All authors have read and agreed to the published version of the manuscript.

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