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Effect of horizontal and radial airflow fans on the microclimate of single-span greenhouses and their yield

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Greenhouse technologies enable the cultivation of horticultural species regardless of their geographical location (Kumar *et al.* 2021). The greenhouse structure facilitates control over climatic factors such as temperature, relative humidity (RH), carbon dioxide (CO_2) concentration, solar radiation (SR) and vapour pressure deficit (VPD), either partially or entirely, to optimize crop yields (Sagar and Singh 2023). Ventilation is primarily employed to manage the quality of indoor air by diluting and replacing the air inside a room, thereby modifying the temperature, RH, and airflow to achieve satisfactory thermal conditions. Proper greenhouse microclimate and ventilation control reduces the need for excess of pesticides and herbicides, conserves water, and reduces energy usage, all of which are crucial in modern commercial farming (Akrami *et al.* 2020). The placement of fans creates air movement that mixes the air, and facilitates the evaporation of moisture from leaf surfaces to lower the risk of disease and also essential to achieve uniformity in crucial factors such as temperature, RH, VPD, and CO_2 level within greenhouses (Akpenpuun *et al.* 2022, Randhe *et al.* 2022). The most commonly used air circulation fan is the horizontal airflow fan (HAF), which is positioned horizontally above the crops canopy. A more recent innovation is the radial airflow fan (RAF), which is mounted vertically over the crop canopy, with one end extending to the ambient atmosphere. Several studies have focused on HAF and their effects on climatic parameters. However, research is scarce on the use of RAF and their impact on the distribution of microclimatic parameters and crop yield. The objective of this study was to investigate the impact of the RAF on the distribution of micro-environment parameters and strawberry yield and to compare the effectiveness of the HAF and RAF.

This experiment was conducted from January to March 2023 at Sangju Smart Farm Innovation Valley, Sangju-si (36°24′39″N and 128°9′32″E at an altitude of 60 meters amsl) Gyeongsangbuk-do, South Korea, in two arch-shaped greenhouses. The climate of Sangju falls within the humid subtropical category. The greenhouses were positioned in an east-west orientation and covered with two polyolefin layers and a thermal screen layer. They had the same length, breadth, and height of 52.8, 6.8, and 2.5 m, respectively with eaves height of 1.5 m. The heights of the first layer (thermal screen), second layer, and third layer were 2.5, 2.8, and 3.05 m, respectively [Fig. 1(a) and (b)]. In the HAF greenhouse (HAF-GH), the side vents operated automatically and opened when the internal air temperature exceeded the pre-set threshold of 20°C. In contrast to the HAF-GH, the RAF greenhouse (RAF-GH) had closed side vents and featured a chimney-like structure extending to the ambient environment. This design facilitated the exchange of air between the greenhouse and the outside based on preset temperature and humidity settings. The sensors and fans were positioned (Fig. 1c). The details of methodology in Akpenpuun *et al.* (2023) was adopted for this study.

Statistical analysis: The data collected were subjected to descriptive statistics, frequency distribution and analysis of variance to compare the microclimates in HAF-GH and RAF-GH.

Temperature: The daily mean temperature recorded in the HAF-GH, RAF-GH, and outside was 12.87±4.60°C, 14.88±5.89°C, and 1.62±6.51°C, respectively, showing that the temperature variability in the RAF-GH was greater than that in the HAF-GH. The mean daily temperature of 14.88°C

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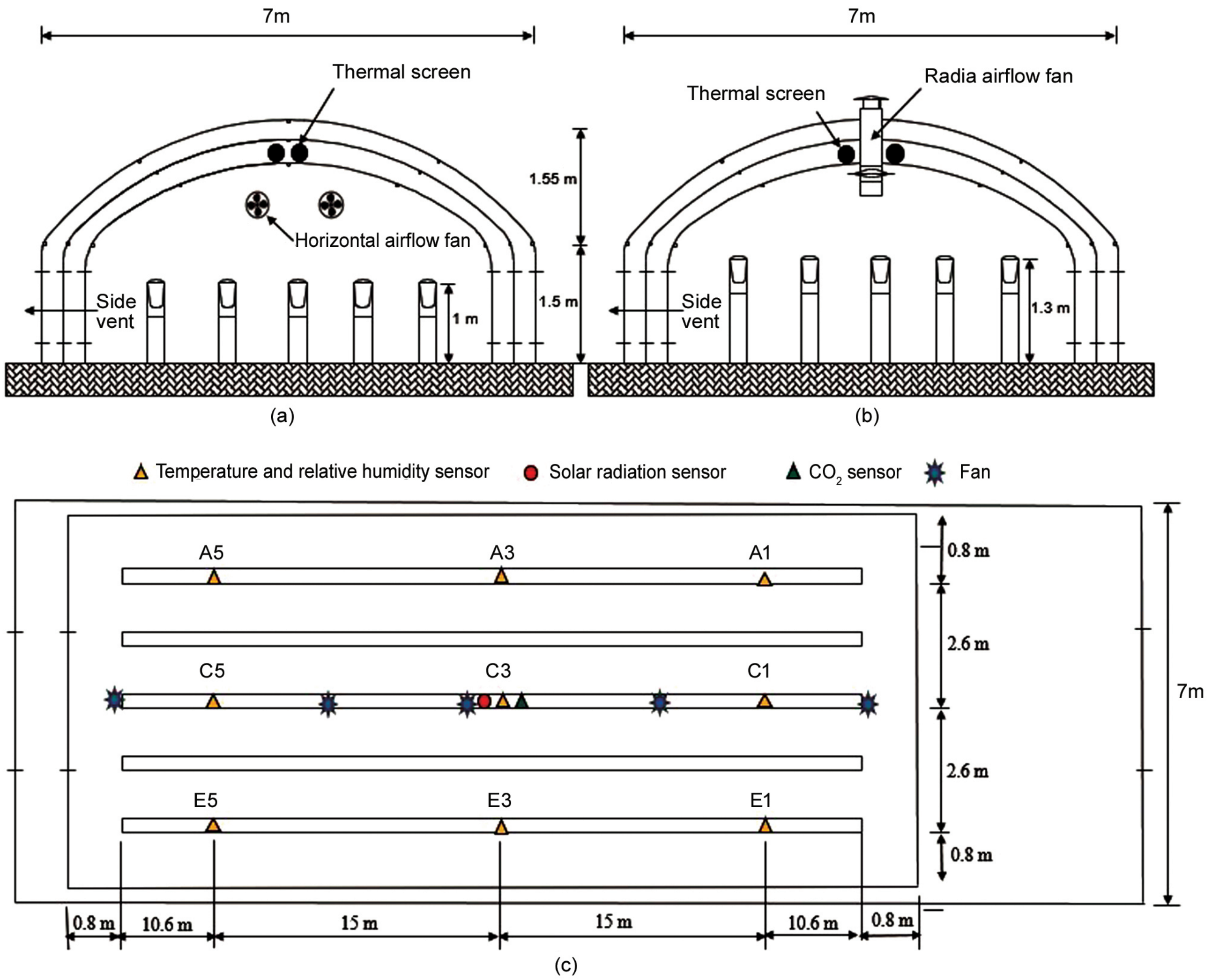

Fig. 1 Cross-sectional view of the experimental (a) horizontal airflow fan (b) radial airflow fan greenhouses, and (c) sensor and fan positions in the greenhouses.

in the RAF-GH aligns with the findings of Nascimento *et al.* (2023), who reported a daily mean temperature of 14.17°C for greenhouse strawberries. The daytime mean temperature was 20.22°C and 16.78°C in the RAF-GH and HAF-GH, respectively. Tang *et al.* (2020) recommended optimal daytime temperature ranges of 18–24°C. Comparatively, the mean night-time temperature was 10°C and 10.96°C in the HAF-GH and RAF-GH, respectively, which is within the range of 10–13°C reported by Ogunlowo *et al.* (2021) as the optimal night-time temperature range. In the HAF-GH, the frequency of the day-time optimal temperature range was 42.29%, whereas it was 43.53% in the RAF-GH. Likewise, the frequency of night-time temperatures within the optimal range in the HAF-GH, was 29.93%, whereas it was 47.98% in the RAF-GH. The analysis has revealed the superiority of the RAF-GH over the HAF-GH for strawberry cultivation.

The ANOVA result (Table 1) suggests a significant difference in the temperature data between HAF-GH and RAF-GH, both during the day- and night-times. Fig. 2 shows the trend of mean hourly temperature variations in both the HAF-GH, RAF-GH, and external environment in January, February, and March. The temperature patterns revealed a gradual increase after 8:00, with peak temperatures between 12:00 and 4:00, followed by a decline during the night-time. Importantly, during day-time, the RAF-GH recorded consistently higher temperatures than the HAF-GH throughout the experiment. In contrast, the HAF-GH recorded slightly lower temperatures during night-time. This temperature discrepancy can be attributed to the distinct ventilation systems employed in the two greenhouses. The radial airflow mechanism used by the RAF ensures a thorough mixing of thermal strata throughout the height of the greenhouse, effectively averaging the temperature. In contrast, the HAF only facilitates mixing at the upper strata levels, as colder air enters through side vents while the warmer air rises toward the greenhouse roof.

Relative humidity: The mean daily RH data was 74.94±16.87%, 83.95±13.57%, and 61.19±19.97% in the HAF-GH, RAF-GH, and external environment, respectively. This shows that RH varied considerably within all three environments, with the external environment showing the widest deviation. Additionally, the mean day-time RH in

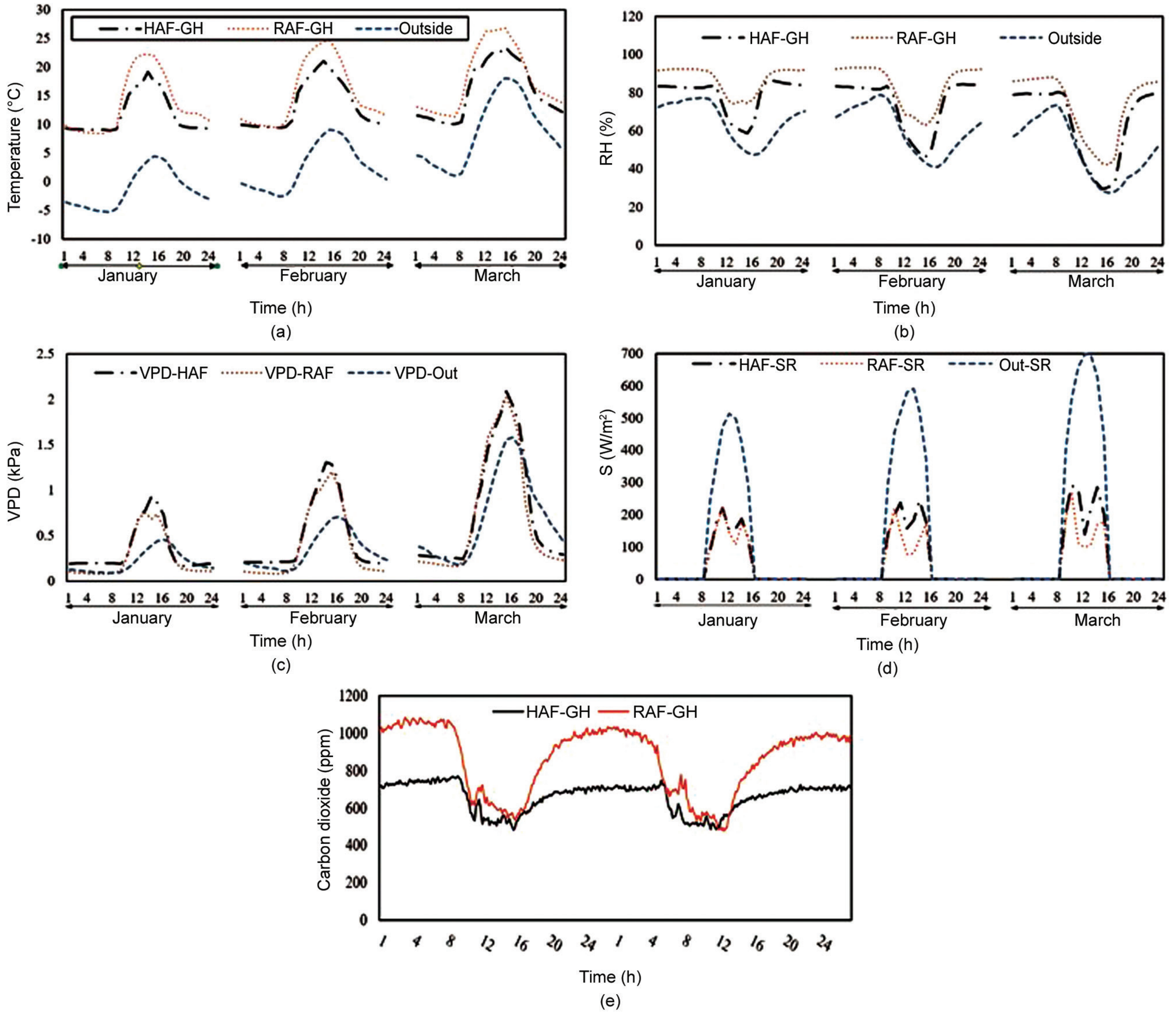

Fig. 2 Mean hourly variation of microenvironment parameters (a) temperature, (b) RH, (c) VPD, (d) SR, and (e) Carbon dioxide in the horizontal airflow fan, radial airflow fan greenhouses, and external environment.

the HAF-GH, RAF-GH, and external environment was 64.44, 74.21%, and 53.20%, respectively. Moreover, the mean night-time RH was 82.67%, 91.11%, and 67.07% in the HAF-GH and RAF-GH and external environment, respectively. Sim *et al.* (2020) and Khammayom *et al.* (2022) reported RH 73.7 to 93.2% and 30 to 93%, respectively while cultivating strawberries in double-layer greenhouses. The day-time RH frequency in the HAF-GH, and RAF-GH was 52.01 and 65.34% respectively within the optimal RH range of 60–90%. During night-time, the frequency of RH falling within the optimal range in the HAF-GH was 88.79%. In contrast, the RAF-GH recorded a lower

Table 1 ANOVA of day and night time temperature (T), RH, VPD, SR, and CO_2 between HAF-GH and RAF-GH at 95% confidence intervals

Greenhouse	Parameter	Day-time			Night-time		
		F-statistics	*P*-value	F-critical	F-statistics	*P*-value	F-critical
HAF-GH vs RAF-GH	T	1080.12	$P<0.01$	3.84	692.57	$P<0.01$	3.84
	RH	588.75	$P<0.01$	3.84	8178.56	$P<0.01$	3.84
	VPD	17.60	$P<0.01$	3.84	25.44	$P<0.01$	3.84
	SR	183.35	$P<0.01$	3.84			
	CO_2	203.56	$P<0.01$	3.84			

frequency (31.99%) of RH falling within the optimal range. The result strongly indicated a notable dissimilarity in RH between the two greenhouse environments during both day and night times. This divergence in RH profiles can be attributed to the distinct ventilation systems employed in the two greenhouses. These findings underline the distinct RH dynamics between the two environments during the night, with RAF-GH displaying a more pronounced tendency toward elevated humidity levels beyond the optimal range.

Vapour pressure deficit: The observed VPD patterns in HAF-GH and RAF-GH (Fig. 2) revealed a gradual increase after 8:00, reaching the highest value between 12:00 and 16:00. In March, during peak hours, the VPD exceeded 1.5 KPa in HAF-GH, RAF-GH, and the external environment. The HAF-GH and RAF-GH maintained a VPD daily range of 0.03 to 3.42 KPa and 0.02 to 2.66 KPa, respectively. Furthermore, the mean day- and night-time VPD was 0.78 KPa and 0.19 KPa, respectively, in the HAF-GH, 0.73 KPa and 0.10 KPa, respectively, in the RAF-GH. Sultan *et al.* (2021) recommended a VPD range of 0.45 to 1.25 KPa as suitable for most greenhouse crops for promoting normal growth throughout the crop cycle. The HAF-GH had 3.07% fewer VPD readings within the recommended range than the RAF-GH, indicating that the conditions in the RAF-GH were more conducive to strawberry production. The ANOVA of the VPD data (Table 1) in the HAF-GH and RAF-GH showed that two environments were significantly different. The data strongly indicated dissimilarity in the VPD data between the two greenhouse environments during day and night-time.

Solar radiation (SR): The descriptive analysis showed that the mean solar radiation was 182.21±103.59 W/m², 145.51±102.75 W/m² and 457.73±213.91 W/m² in the HAF-GH, RAF-GH, and external environment, respectively. The maximum value of SR was 448.68 W/m², 503.73 W/m², and 856.98 W/m² in the HAF-GH, RAF-GH, and external environment, respectively. The HAF-GH had a frequency of 5.45% and the RAF-GH had a slightly lower frequency of 4.42% falling below the range of 21.73–65.21 W/m^2 recommended for strawberry cultivation by Yoshida *et al.* (2016). Tang *et al.* (2020) reported an optimal solar radiation range of 73.8 to 98.43 W/m² for quality strawberries. The frequency of SR values falling within the recommended range was 7.69% and 18.53%, respectively, in the HAF-GH and RAF-GH. The ANOVA of SR (Table 1) of HAF-GH and RAF-GH showed significant differences in SR in the two greenhouse environments. The minimum hourly mean SR values for January, February and March were 89.14, 139.31 and 139.50 W/m², respectively, for HAF-GH. In contrast, the corresponding values of SR in the RAF-GH were 105.40, 78.53 and 98.76 W/m² for the same respective months.

Carbon dioxide: The mean daily carbon dioxide in the HAF-GH and RAF-GH was 643.12±121.65 ppm and 801.05±243.13 ppm, respectively. Throughout the experiment, RAF-GH consistently maintained higher CO_2 levels than HAF-GH. Notably, these values of CO_2 exceeded the 600 ppm threshold associated with the peak photosynthesis rate, as recommended by Sim *et al.* (2020). The frequency of CO_2 levels within the range of 600–900 ppm was 33.19% in RAF-GH, which was slightly higher than 30.56% recorded in the HAF-GH. The ANOVA of CO_2 (Table 1) in the day and night-time data in the HAF-GH and RAF-GH showed that the two environments were statistically significantly different.

Yield: The total strawberry yield in the HAF-GH was 328 kg, while the total yield in the RAF-GH was 445 kg. The difference between the yield in the RAF-GH and HAF-GH was 117 kg in favour of RAF-GH. The yield data indicate that under identical greenhouse conditions, RAF can produce more uniformly blended air.

SUMMARY

The present study evaluated and compared the distribution patterns of microclimatic parameters within greenhouses to provide insights into optimizing growing conditions and maximizing crop productivity. Experiments were conducted from January to March 2023 at Sangju Smart Farm Innovation Valley, Sangju-si, South Korea, in two adjacent greenhouses covered with two polyolefin layers and a thermal screen layer. The distinctive design of the radial airflow fan connecting to the external environment and ability to uniformly blend air, demonstrated superior performance than the horizontal air flow fan. The adoption of radial airflow fans could greatly influence commercial production by enhancing the distribution of microclimate variables, resulting in improved greenhouse efficiency and ultimately leading to increased crop yields.

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