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Simulation and validation of the effect of horizontal and radial airflow on the microclimate of single-span greenhouses using CFD

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ABSTRACT

Greenhouse technology provides a controlled environment that optimizes crop production, especially under adverse conditions. Ventilation systems are essential for regulating the microclimate, affecting temperature, humidity, and gas exchange. This study evaluated the effectiveness of horizontal airflow (HAF) and radial airflow (RAF) fans in managing microclimate conditions within single-span greenhouses, utilizing Computational Fluid Dynamics (CFD) simulations for simulation while the data from the field experiment was used to validation. Temperature and relative humidity were collected from sensors positioned at various points within the greenhouses. The results indicated that RAF-GH maintained a higher mean temperature (14.88 °C) than HAF-GH (12.87 °C), leading to a more stable thermal environment conducive to crop growth. Additionally, RAF-GH exhibited higher consistent relative humidity levels, averaging 83.95 %, while HAF-GH recorded 74.94 %. CFD simulations revealed that RAF systems achieved more uniform temperature and humidity distributions than HAF systems, thereby offering a better environmental control. The simulations closely mirrored field experiment, confirming the accuracy and reliability of CFD modeling in predicting greenhouse conditions. The study concludes that RAF systems are more effective than HAF systems for maintaining optimal greenhouse conditions.

Keywords: Greenhouse technology, Microclimate regulation, Horizontal airflow fans (HAF), Radial airflow fans (RAF), Computational Fluid Dynamics (CFD)

INTRODUCTION

The increase in the global population, conflicts worldwide and climate change combined with the rising cost of energy, have rendered traditional process of food production insufficient and inefficient in meeting the global food demand. These challenges necessitated the need to develop technologies that can be used for food production anywhere around the world in a controlled environment protected from adverse climatic conditions, and with efficient use of energy. Greenhouse technology has completely transformed modern agriculture by offering a regulated environment that promotes ideal plant growth and development (Li et al., 2018). The utilisation of greenhouses offers numerous advantages., these include the extension of the growing season, protection of crops from unfavourable climatic conditions, and maximising a range of environmental factors like temperature, humidity, and light intensity (Singh et al., 2024). Farmers may grow a variety of crops year-round in this controlled environment, which boosts output overall and promotes food security (Vatista et al., 2022).

Greenhouse microclimate conditions must be effectively managed to maximise crop yields and quality. The term "microclimate" describes the climate inside a greenhouse structure. These are influenced by ventilation, heating, and cooling systems (Akpenpuun et

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al., 2022). Inadequate ventilation can lead to the accumulation of heat moisture and airborne pathogens. This adversely affects plant health and productivity (Tekai et al., 2010).

Temperature regulation is essential in greenhouse environments as it directly influences plant physiological processes growth rates and overall productivity (Park et al., 2015). High temperatures can induce heat stress. This impairs photosynthesis respiration and transpiration rates. It leads to reduced growth and yield (Harel et al., 2014). Conversely, low temperatures can inhibit metabolic activities. They delay plant development, particularly in tropical regions where cold stress may occur (Nascimento et al., 2023). Optimal temperature management is crucial for maintaining plant health. It is essential for achieving maximum crop yields within greenhouses. Various strategies are employed to regulate greenhouse temperatures including natural ventilation, evaporative cooling shading systems and supplemental heating (Akpenpuun, 2021). In greenhouse microclimate management, relative humidity is essential because it affects plant transpiration, water intake, and disease susceptibility (Prenger and Ling, 2001). Excessive relative humidity (RH) can foster the growth of fungi that cause botrytis and powdery mildew, which can destroy crops and lower their quality. (Khammayom, 2022). Conversely, low RH levels can result in excessive water loss through transpiration, causing plant wilting and dehydration (Hidaka, 2022). Maintaining optimal RH levels is essential for promoting plant health and minimizing the risk of disease outbreaks. Various methods are employed to control RH within greenhouses, including natural ventilation, dehumidification systems. Vapor pressure deficit (VPD) is a crucial parameter governing plant water loss and transpiration rates within greenhouses (Thongbai et al., 2010). Optimizing VPD levels is essential for promoting plant growth and minimizing water stress within greenhouse environments (Telias et al., 2011). Ventilation systems are utilized to control VPD levels by adjusting airflow rates and humidity levels within the greenhouse (Shamshiri, 2018). By maintaining optimal VPD ranges, growers can ensure efficient water use and nutrient uptake while minimizing the risk of water stress-induced crop losses.

Adequate air circulation is essential for maintaining uniform microclimate conditions within greenhouses, ensuring optimal temperature, humidity, and gas exchange (Azaza, et al., 2016). Stagnant air pockets can lead to temperature differentials, humidity gradients, and disease proliferation, negatively impacting plant health and productivity (Kuroyanagi, 2016).

The most commonly used fan for circulating air is the horizontal airflow fan (HAF). This fan is placed horizontally above the crop canopy. A newer type is the radial airflow fan (RAF), which is mounted vertically over the crop canopy with one end reaching into the surrounding atmosphere (Dutta, et al., 2024). They also prevent the buildup of stagnant air pockets (Kuroyanagi, 2016).

Computational Fluid Dynamics (CFD) serves as a valuable tool for accurately predicting different climates within greenhouses (Valentin et al., 2021). CFD simulations enable researchers to visualize and quantify the impact of different ventilation strategies on temperature distribution, airflow velocity, and humidity levels. By integrating CFD simulations with experimental data, researchers can develop robust models for optimizing greenhouse design and management practices (Yoon et al., 2020).

The comparative effectiveness of these fan systems in greenhouse microclimate management remains an area of active research. This study is aimed at assessing the effectiveness of horizontal and radial airflow fans in regulating the microclimate parameters within single-span greenhouses using computational fluid dynamics (CFD) simulation.

MATERIALS AND METHODS

This experiment took place in two tunnel greenhouses from January to March 2023. The greenhouses were positioned in an east-west orientation. The arch-shaped greenhouses were covered with two layers of polyolefin and a layer of thermal screen. Both greenhouses had the same length, breadth, and height of 52.8 m, 6.8 m, and 2.5 m, respectively, and had eaves height of 1.5 m. The heights of the first layer (thermal screen), second layer, and third layer were 2.5 m, 2.8 m, and 3.05 m, respectively. The polyethylene film had a thickness of 200μm and a transmittance of 91 %. The thermal screen had a thickness of 3.5 mm, a conductivity of 0.037 Wm^{-1} K^{-1}, a transmittance of 0.001, a reflectance of 0.1, and an emittance of 0.90.

Table 1: Greenhouse specifications.

Parameter	HAF-GH	RAF-GH
Span	Single	Single
Glazing type	PE (Double layer)	PE (Double Layer)
Dimension	52.8m*6.8m*2.5m	52.8m*6.8m*2.5m
Fan type	Horizontal airflow	Radial airflow
Number of fans	5	5
Crop Type	Strawberry	Strawberry

The horizontal airflow greenhouse (HAF-GH) was equipped with five horizontal airflow fans, also operating at a voltage of 220 V and a frequency of 60 Hz. These fans have a window size, wing diameter, an allowable fan capacity, a maximum speed and a power rating of 25 cm, 23 cm, 0.2 A, 1500 m^3h^{-1}, and 0.54 hp, respectively. Similarly, the radial airflow greenhouse (RAF-GH) was equipped with five radial airflow fans with 30 cm and 28 cm window size and wing diameter, respectively. Each operated at a voltage of 220 V and a frequency of 60 Hz. These fans have an allowable fan current rating, maximum speed, and power rating of 1.16 A, 2290 m^3h^{-1}, and 4.43 hp, respectively. The spacing between the fans was approximately 13.2 m. In the HAF-GH, the side vents operated automatically, opening when the internal air temperature exceeded the pre-set threshold of 20 °C. In contrast, the RAF-GH adopted a different strategy. In RAF-GH, a radial airflow fan had a chimney-like structure that extended to the ambient environment. To maintain the optimal range of air temperature within the greenhouses during the winter, a heating system comprising a boiler and heat dissipaters was used. Similarly, the radial airflow greenhouse (RAF-GH) was equipped with five radial airflow fans with 30 cm and 28 cm window size and wing diameter, respectively. Each operates at a voltage of 220 V and a frequency of 60 Hz. These fans have an allowable fan current rating, maximum speed, and power rating of 1.16 A, 2290 m^3h^{-1}, and 4.43 hp. The spacing between the fans was approximately 13.2 m. In the HAF-GH, the side vents operated automatically, opening when the internal air temperature exceeded the pre-set threshold of 20 °C. In contrast, the RAF-GH adopted a different strategy, a radial airflow fan with a chimney-like structure that extended to the ambient environment. To maintain the optimal range of air temperature within the greenhouses, a heating system comprising a boiler and heat dissipaters was used during the winter. The portions in green and yellow shades are the same. Please delete the yellow shaded portion.

Temperature and RH of the greenhouse air were measured during the daytime and nighttime. Three sensors of air temperature and relative humidity were installed at 1.54 m from the greenhouse floor per row (front, centre, and end) (accuracy: 0.25 °C, HOBO

PRO v2 U23 Pro v2, ONSET, 3 min in air moving 1 ms^{-1}; 30 s in stirred water, USA), resulting in 15 sensors per greenhouse This methodology is the same as that used in (Dutta et al., 2024). The two ventilation systems were simulated using CFD tools with the given parameters of the greenhouses and the results were collected. The data collected from the real-time experiment and CFD simulation were analysed and compared to determine the effectiveness of the two ventilation systems and also the accuracy of CFD in predicting the microclimate condition in a greenhouse under the given conditions. Figure 1 shows the (a) horizontal airflow fan (b) radial airflow fan greenhouses, and (c) sensor and fan positions in the greenhouses.

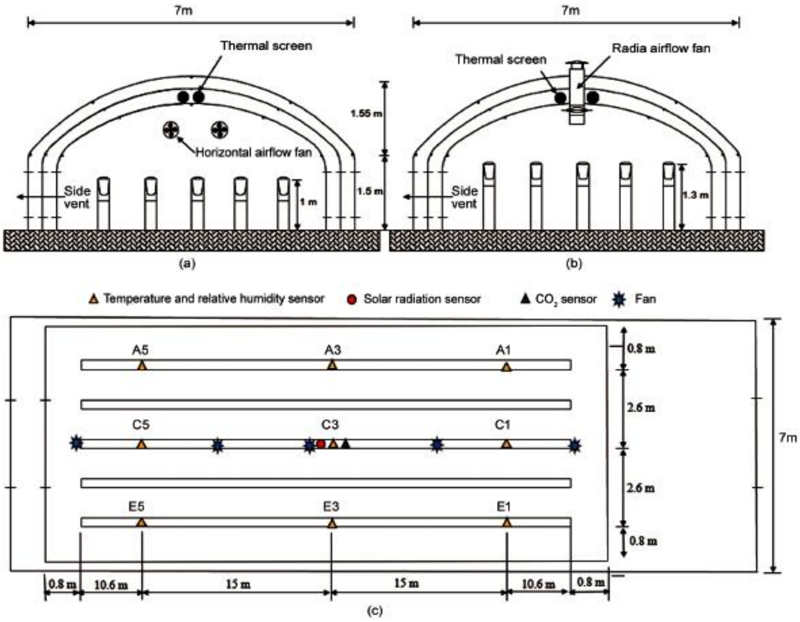

Figure 1: Cross-sectional view of the experimental (a) horizontal airflow fan (b) radial airflow fan greenhouses, and (c) sensor and fan positions in the greenhouses.

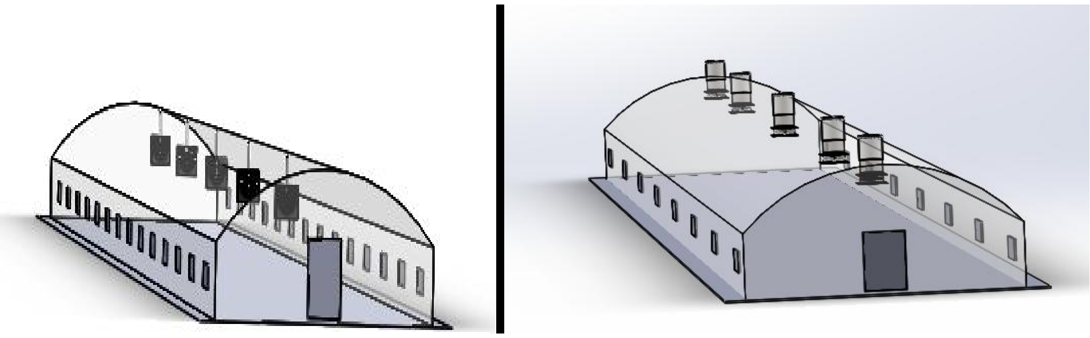

Figure 2: HAF and RAF greenhouse CFD models

The Pre-simulation Stage

This stage includes 3D modeling or creating a geometric representation of the parts to be analyzed in SOLIDWORKS. These parts were first sketched in 2D and then features like Extrude, Revolve Sweep and Loft were used to convert the 2D sketches into 3D models. At this stage, it is important to ensure all dimensions and geometric features are properly defined to maintain design intent. After 3D modeling is assembling of the different components. This involves combining parts into a single assembly to represent a complete system using mates

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(constraints) to define relative positions and movements of components. This ensures that all parts fit together as intended and that assembly behaves as expected. The definition of the axis of rotation and rotating speed of any components that required rotation such as fan blades was done at this stage and ensuring that rotating regions/components are properly defined to interact correctly with surrounding parts. Figure 2 shows the Flowchart for simulation process.

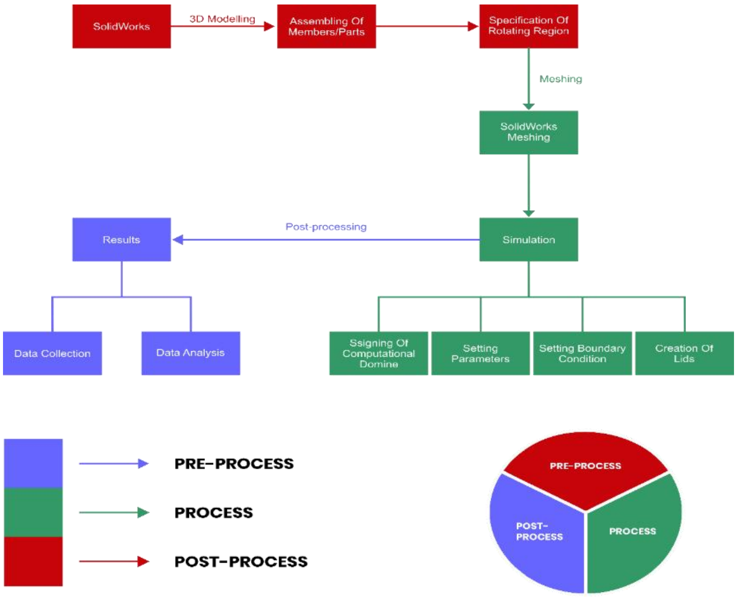

Figure 3: Flowchart for simulation process.

RESULTS

CFD simulation temperature

The spatial distribution of temperature within the greenhouse is presented in Figure 4. The results indicated that, the RAF system maintains a more uniform temperature distribution compared to the HAF system, which showed pockets of higher and lower temperatures. The uniform temperature distribution is critical for ensuring all strawberry plants received the same growing conditions, leading to uniform growth and fruit quality.

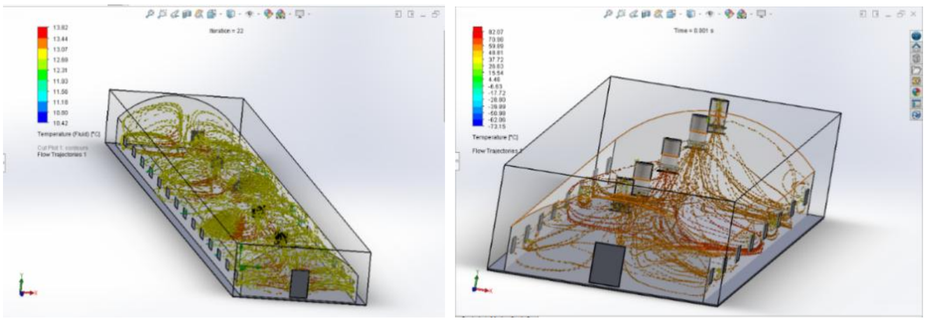

Figure 4: Temperature distribution in the two systems

Also, table 2 shows the descriptive statistics of temperature in both systems. The HAF system results in a lower mean temperature (11.13 °C) compared to the RAF system (12.81 °C). However, the HAF system exhibits a significantly higher standard deviation (1.60) and variance (2.55), indicating greater temperature fluctuations.

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These fluctuations can affect the growth and development of strawberries, as consistent temperatures are crucial for maintaining optimal physiological processes in the plants.

Table 2: Descriptive statistics of simulated temperature

Statistic	RAF-GH	HAF-GH
Mean (°C)	12.81	11.13
Standard Deviation	0.14	1.60
Sample Variation	0.02	2.55
Minimum (°C)	12.32	8.03
Maximum (°C)	12.96	13.62

Validation

The validation of the microclimate conditions of the two greenhouse types: Horizontal Air Flow (HAF-GH) and Radial Air Flow (RAF-GH) was carried out. Figure 5 shows the temperature profile in the HAF and RAF. The validation showed that the RAF-GH maintained a higher mean temperature and greater temperature variability compared to the HAF-GH, with mean temperatures of 14.88 °C and 12.87 °C, respectively. The RAF-GH also exhibited higher daytime temperatures, contributing to a more stable thermal environment conducive to crop growth. The 24-hour temperature patterns revealed that the RAF-GH consistently recorded higher temperatures during daylight hours, while the HAF-GH had slightly lower nighttime temperatures due to its distinct ventilation system. The difference between the simulated and validated temperature in the HAF-GH and RAF-GH was 2.07 °C and 1.74 °C, respectively.

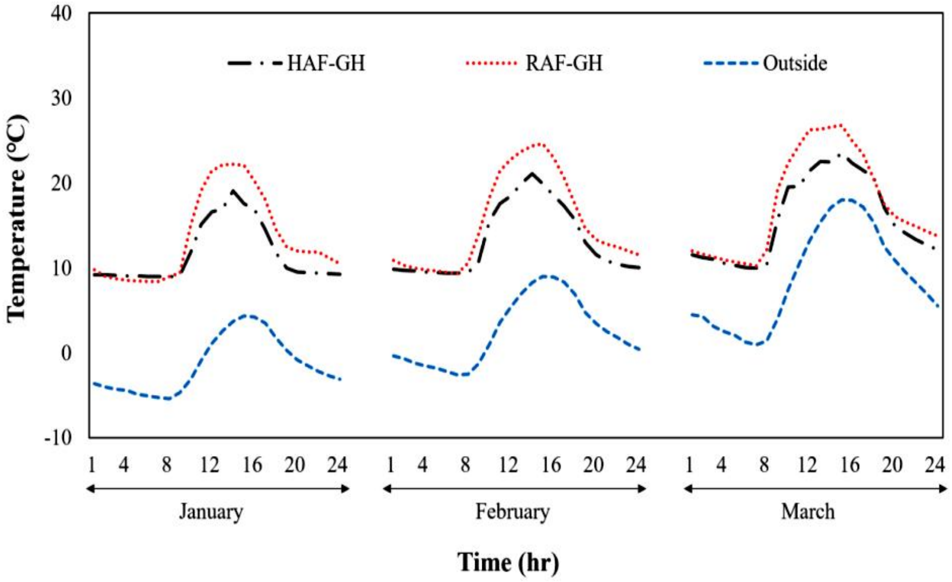

Figure 5: Temperature Variations in HAF-GH RAF-GH and Outside

Humidity Distribution

Figure 6 shows the spatial distribution of humidity within the greenhouses. It can be observed that the RAF system maintained a higher and more uniform humidity distribution compared to the HAF system, which showed slightly more variation. Uniform humidity levels are essential for preventing fungal diseases, which can be a significant issue in strawberry cultivation if some areas are more humid than others.

The humidity distribution within the RAF-GH and HAF-GH systems is presented in Table 3. The results indicated that, the RAF system achieved a higher mean humidity level (99.92 %) compared to the HAF system (76.69 %). The standard deviation and range of humidity values were relatively small for both systems, suggesting that both

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systems maintain consistent humidity levels. High humidity is beneficial for strawberry plants as it reduces transpiration rates and helps maintain turgor pressure in the plants, which is vital for cell expansion and fruit development (Katsoulas and Kittas, 2009).

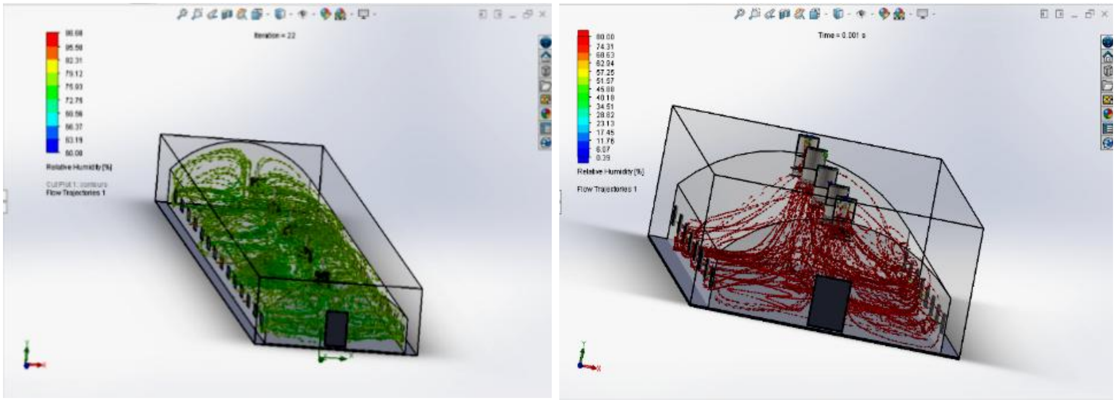

Figure 6: Humidity distribution in the two systems

Table 3: Descriptive statistics of simulated humidity.

Statistic	RAF-GH	HAF-GH
Mean (%)	99.92	76.69
Standard Deviation	0.23	0.63
Minimum (%)	98.82	76.11
Maximum (%)	100	78.94

Relative humidity (RH) levels were also analyzed, showing that the RAF-GH had a higher and more stable RH compared to the HAF-GH. The mean 24-hour RH was 83.95 % in the RAF-GH and 74.94 % in the HAF-GH. During the daytime, the RAF-GH maintained higher RH levels, with 65.34 % of the data falling within the optimal range of 60-90 %, compared to 52.01 % in the HAF-GH. The nighttime RH was similarly higher in the RAF-GH, ensuring a more humid environment throughout the experimental period. This stability in RH can be attributed to the enhanced ventilation system of the RAF-GH, which contributed to better moisture retention and potentially improved plant health. Figure 7 shows the pattern of RH distribution in both greenhouses and the ambient environment.

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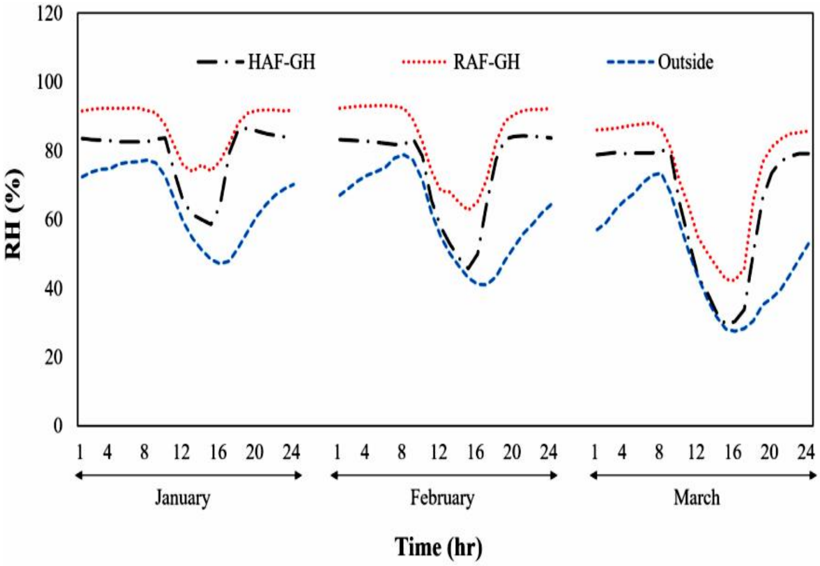

Figure 7: Relative humidity variations in HAF-GH, RAF-GH, and outside.

Table 4 shows that the CFD simulated temperature in the RAF-GH system was 12.81 °C, which corresponds with the field experiments' nighttime temperature range of 10.0-13.0 °C. HAF-GH, on the other hand, recorded a slightly lower mean nighttime temperature of 11.13 °C, also within the range of 10.0-13.0 °C, but with a frequency of 47.98%, higher than the 29.93% observed in the RAF-GH. These findings show that the simulation results were consistent with the field experiment outcomes. For the daytime temperature ranges, the HAF-GH and RAF-GH recorded 54.26% and 30.91%, respectively, of the data within the range of 0-17 °C. The simulated result, however, was 11.13 °C, which fell within the same range (0–17 °C) that had the highest frequency. The humidity range of 60 – 90% was observed with frequencies of 65.34% and 52.01%in the RAH-GH and HAF-GH, respectively. The field and simulated result showed that the RAF-GH provided an environment with higher humidity during the daytime, contributing to better temperature regulation and creating a more favorable daytime environment compared to the HAF-GH. The overall trend showed that the RAF-GH performance better, both daytime and nighttime, in maintaining desired environmental conditions compared to the HAF-GH. Computational Fluid Dynamics (CFD) simulation has proven to be an invaluable tool for evaluating and optimising the dynamic and complex greenhouse microclimates, as evidenced by its accuracy and reliability as observed in this study.

Table 4: Data from Real-time Experiment and CFD Simulation.

Parameter	**Day-time**			**Night-time**				
	Frequency %				**Frequency %**		**CFD**	
	Range	**HAF-GH**	**RAF-GH**	**Range**	**HAF-GH**	**RAF-GH**	**HAF-GH**	**RAF-GH**
T (°C)	0 - 17	54.26	30.91	0 - 9	64.61	36.39	11.13	12.81
	18 - 24	42.29	43.53	10.0 - 13.0	29.93	47.98		
	24+	3.44	25.56	13+	5.47	15.63		
RH (%)	0 - 59	41.24	17.94	0 - 59	0.14	0.02	76.11	99.92
	60 - 90	52.01	65.34	60 - 90	88.79	31.99		
	90+	6.75	16.73	90+	11.07	67.99		

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DISCUSSION

Temperature Distribution

The RAF system showed a higher mean temperature of 12.81°C with minimal variability, indicating a stable thermal environment. The uniformity in temperature within the greenhouse environment is essential for plant physiological processes, including photosynthesis and respiration, as noted by Harel et al. (2014). The findings support the significance of temperature stability for strawberry cultivation, as fluctuations can impair growth and fruit quality. Similar to the observations of Tang et al. (2020), the RAF system’s capability to maintain a uniform temperature distribution directly significantly enhances plant productivity. In contrast, the HAF system showed a notable temperature variability, potentially resulting in uneven growth, as evidenced by previous research on greenhouse temperature management (Li et al., 2018). The standard deviation and variance in the HAF system recorded was 1.60 and 2.55, respectively, suggestting suboptimal environmental control, as previously reported by Shamshiri et al. (2018). This aligns with prior research emphasizing the critical role of uniformity in temperature and humidity distributions for optimal crop growth and health (Akpenpuun et al., 2022; Valentin et al., 2021).

Humidity Regulation

The RAF system achieved a mean relative humidity (RH) of 99.92%, revealing a greater stability compared to the HAF system's mean of 76.69%. Elevated relative humidity is advantageous for reducing plant transpiration rates and sustaining turgor pressure, as noted by Prenger and Ling (2001). The findings are consistent with Shamshiri et al. (2018), who emphasized the role of stable relative humidity in minimizing water stress and enhancing nutrient absorption. The study also revealed that the RAF system significantly reduce spatial variations in RH, which is critical in preventing fungal diseases like Botrytis and powdery mildew, as reported in Khammayom et al. (2022). The stable relative humidity levels achieved by the RAF system showed an enhanced environment control, consistent with Kuroyanagi's (2016) research on the efficacy of advanced ventilation strategies.

Verification of CFD Simulations

The strong correlation between CFD simulations and experimental data showed the reliability of CFD modeling in greenhouse microclimate optimisation. Valentin et al. (2021) and (Rasheed *et al.*, 2019) reported that CFD simulations offer valuable insights into airflow dynamics and environmental conditions, facilitating precise design and management decisions. This research has shown that CFD is an effective tool in simulating real-world scenarios and optimizing greenhouse designs and configurations (Yoon et al., 2020).

Implications for Greenhouse Management

The results have shown that selecting the most appropriate ventilation systems guarantees consistent environmental conditions of the greenhouse environment. In other words, the results of this study highlight the superiority of radial airflow fans (RAF) over horizontal airflow fans (HAF) in regulating greenhouse microclimate conditions. The RAF system did not only enhance microclimate stability but also improve plant health and productivity by reducing environmental stressors. These findings align with Kumar et al. (2021), who emphasized the role of advanced ventilation systems in modern greenhouse management. In addition, the use of CFD modeling enhances decision-making by providing detailed analyses of microclimate dynamics, as noted by (Akpenpuun *et al.*, 2021).

CONCLUSION

This study evaluated and compared the effects of Radial Air Flow (RAF) and

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Horizontal Air Flow (HAF) fan systems on the microclimate within a single-span greenhouse, specifically focusing on the cultivation of strawberries. Computational Fluid Dynamics (CFD) was used to simulate the microclimate condition of the greenhouses. The Radial Air Flow (RAF) fan system showed more consistency in maintaining the microclimate condition in the greenhouse which is suitable for the cultivation of strawberries. Also, the simulation results closely mirrored those of the field experiment, highlighting the accuracy and reliability of CFD in replicating complex environmental conditions.

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