Effect of Thermal Screen Position on Greenhouse Microclimate and Impact on Crop Growth and Yield

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ABSTRACT: Worldwide, researchers are developing methods in which producers can obtain higher yields and conserve more energy in greenhouse crop cultivation. To achieve this, thermal screens are deployed during cold nights and rolled up during the daytime. The positioning of these screens causes a reduction in the amount of solar radiation (SR) received by greenhouses, especially the single span. The impact of thermal screen position on the receipt of SR, temperature, relative humidity (RH), vapour pressure deficit (VPD), fuel consumption, and the consequent effects on crop yield and growth were investigated in this study. Two greenhouses with similar dimensions and structure but different thermal screen positions were designed, namely R-greenhouse (RGH) with thermal screens at the centre of the roof and Q-greenhouse (QGH) at five degrees (5^o) Northward. Strawberries were cultivated as study crops. Statistical analysis of the recorded data of greenhouse microclimate parameters, crop growth, and yield showed that both greenhouses performed similarly in energy savings, and there was no significant difference regarding temperature, RH, and VPD. However, there were significant differences in the crop growth and yield obtained in the QGH compared to RGH. This can be attributed to the higher amount of SR received by the QGH than the SR that was received by the RGH, which was achieved because the thermal screen was installed on the north side of the Q greenhouse.

KEYWORDS: Solar radiation Energy consumption, Crop growth, Crop yield, Thermal screen position, Greenhouse microclimate

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I. INTRODUCTION

Global population growth compared to current food production and supply has necessitated the practice of agricultural innovations, such as greenhouses and plant factories, and their management techniques. Productivity, efficient use of resources, high demands for quality agricultural products, and environmental impacts are the major factors that need to be considered in transforming current food production systems (Willett *et al*., 2019; Adesanya *et al*., 2022). Therefore, innovative greenhouse production has significant potential in terms of economic and year-round production capabilities with increased productivity, increased production per land, water and nutrient units, higher fruit quality, enhanced production for each unit of water and nutrient, more extended production periods, and off-season production (Abdrabbo *et al*., 2019; Akpenpuun and Mijinyawa, 2020). The greenhouse cultivation approach aims to create near-optimal microclimatic conditions for growing crops and shielding crops from adverse ambient conditions. In addition to protection from adverse conditions, indoor growing modules have some advantages over open-field cultivation, including (i) increased off-season vegetable production, (ii) buffering against external weather conditions, and (iii) providing better conditions for crop growth and development than outdoor conditions (Mijinyawa, 2011; Bisbis *et al*., 2018). Furthermore, greenhouses provide a bridge between planting in adverse cold weather conditions, such as winter in temperate countries like South Korea, or adverse hot weather conditions, such as the dry season in tropical countries like Nigeria, thereby providing season-long crop production.

Environmental parameters such as temperature, relative humidity (RH), vapour pressure deficit (VPD), carbon dioxide (CO2) concentration, and solar radiation (SR) and their distribution in the greenhouse influence crop production

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(Shamshiri *et al.*, 2018; Ogunlowo *et al*., 2021; Akpenpuun *et al*., 2022). The individual relationships and mutual interactions among these parameters affect critical plant processes, such as photosynthesis, respiration, transpiration, growth, development, and yield. In addition, greenhouse microclimate conditions, most importantly air temperature and photoperiod, VPD, and CO2 concentration, impact the organoleptic and functional quality of greenhouse vegetables (Wang *et al*., 2008; Akpenpuun and Mijinyawa, 2018).

The optimal growth and development of a plant in a greenhouse depend on the greenhouse temperature; hence, its control within the greenhouse is paramount. The temperature is affected by sunlight penetration into the greenhouse through the transparent roof and walls and the prevention of thermal leakage by the cover material. This mechanism increases the inside temperature relative to the outside temperature (Giacomelli, 2009; Vadiee and Yaghoubi, 2016). Temperature significantly influences the growth and development of greenhouse crops. Optimisation of greenhouse air temperature will enable optimal growth of most greenhouse vegetables, leading to high yields. In general, the optimum temperature range for the growth of most greenhouse vegetables is 18.3 – 32.2 oC as the temperature significantly affects biomass production and partitioning, development, and the fruit growth period (Shamshiri *et al*., 2018; Palmitessa *et al*., 2020). High-temperature levels in the greenhouse harm the plant by reducing the capacity and quality of the plant's production. Maintaining the temperature in the greenhouse at optimal levels is challenging, especially during the winter season in temperate regions; hence, there is a need for a sound heating system whose primary heating source is the burning of fossil fuels and grid electricity (Bartzanas *et al*., 2005). VPD is the difference between the saturation vapour pressure and the actual vapour pressure, which are derivatives of air temperature and relative humidity. VPD provides a relatively accurate indication of greenhouse plant conditions because of the combined effects of relative humidity and temperature in its estimation (Wollaeger and Runkle, 2017; Akpenpuun *et al*., 2021a). A low VPD tends to promote the spread of diseases due to films or dew on plant leaves, the inner surface of the covering material, or the inner surface of the thermal screen of a greenhouse with a thermal screen. High VPDs increase plants' minerals and water absorptive capacities, resulting in high transpiration and evaporation. In other words, a high VPD is equivalent to low relative humidity and vice versa.

VPD in the range of 0.8 - 1.0 kPa is ideal for the optimal growth of greenhouse plants (Na Lua *et al*., 2015; Amani *et al*., 2020). Solar and thermal radiation exchanges dominate the energy transfer processes in greenhouses. Solar radiation also provides photon energy plants need to photosynthesise for growth and development (Larcher, 2003). Photosynthesis is driven by radiation with wavelengths of 400–700 nm. The internal greenhouse irradiance is usually sufficient for crop production (Giacomelli and Roberts, 1993), even though it is typically lower than the ambient irradiance because of reflection, partial scattering, and refraction of incident radiation by the cover material. Hence, consideration is given to the transmittance property of solar radiation of a greenhouse covering material, as the purpose of greenhouse covering is to create an internal environment suitable for plant growth. Zhao *et al*. (2001) also reported that the physical structure of the greenhouse, such as the angle and shape of the roof, the number and width of the spans (distance from the gutter to the gutter in the case of multi-span), the height of the end walls, the length-to-width ratio of the structure, and the compass orientation, influence radiation transmission and distribution within the greenhouse. Chen *et al*. (2018) reported the suitability of greenhouse orientation at different latitudes owing to the variability of the solar trajectory and radiation intensity. In this context, it is recommended that the east-west direction is in the best position for maximum reception and distribution of solar radiation (Panwar *et al*., 2011; Akpenpuun *et al*., 2021a).

Energy-saving technologies are increasingly being used in the greenhouse industry to reduce fossil fuel consumption, which will invariably reduce the cost of greenhouse production. Most heated greenhouses in temperate regions are such that their ventilation rates through leakages are minimised, and thermal screens are installed to conserve energy, as greenhouses lose heat primarily through conduction, convection, and radiation (Hernández *et al*., 2017). The covering material and thermal blankets reduce the heating or cooling needs of greenhouses by increasing their thermal resistance and decreasing the heat transfer rate between indoor and outdoor air (Teitel *et al*., 2009; Rabiu *et al*., 2022). Thermal screens in these greenhouses usually unfold over the crop at sunset and fold at sunrise, although the optimal opening strategy depends on outside weather conditions. Thermal screens save energy but influence the greenhouse microclimate and, therefore, can affect crop behaviour (Katsoulas and Kittas, 2008; Hernández *et al*., 2017; Rasheed *et al*., 2019a; Akpenpuun *et al*., 2021a). Thermal screens can be fixed, immovable, or retractable/movable. Retractable thermal screens can either be retracted to the roof ridge greenhouse or the sidewalls of the greenhouse. Akpenpuun *et al*. (2021a) investigated two single-span greenhouses whose thermal screens retracted to the greenhouse roof ridge and reported that the retracted thermal screens significantly obstructed the incident solar radiation to the greenhouse.

Strawberry (Fragaria ananassa) is a soft fruit crop that belongs to the family Rosaceae and genus Fragaria. Strawberries have a maturity period of approximately 90–120 d after planting (Li *et al*., 2010). Strawberries are economically valuable with highly desirable taste and flavour, and they also contain vitamins, minerals, phenolics, flavonoid fibres, and sugars (Khalid *et al*., 2013; Tang *et al*., 2020). Studies have investigated strawberry fruits' morphology, productivity, and quality (Chaves *et al*., 2017; Tang *et al*., 2020; Sim *et al*., 2020; Akpenpuun *et al*., 2021a). The growth of strawberry plants in greenhouses not only prevents damage from natural causes, but also provides a suitable environment for its growth and development, and, subsequently, its yield (Khoshnevisan *et al*., 2013; Ahn *et al*., 2021). Strawberries are grown in a wide range of production systems to produce high yields of quality fruits with sufficient flexibility to meet market demands and labour availability (Li *et al*., 2010; Jayasekara *et al*., 2018). Strawberries can be cultivated either in an open field or under protection. However, open-field crops are mulched with straw or plastic to aid weed control, conserve soil moisture, control soil temperature, protect roots from cold injury, reduce fruit decay, save irrigation water, and help reduce contamination by keeping the fruit off the soil surface (Mira de Orduna, 2010; Moretti *et al*., 2010).

Several researchers have studied the effects of various environmental parameters on strawberries' growth, development, and yield. For example, Lieten (2002), Khalid *et al*. (2013), Palencia *et al*. (2009), Sim *et al*. (2020), and Akpenpuun *et al*. (2021b) studied the effect of RH on the performance of greenhouse-grown strawberries; the effect of organic amendments on vegetative growth, fruit and yield quality, and yield efficiency of strawberries and their correlation with temperature and solar radiation; developed strawberry yield prediction equations; and the effect of covering material and thermal screen positions on the greenhouse environment, respectively. Other researchers have investigated the effect of humidity on vegetables and ornamental plants and reported that high humidity enhances vegetable growth, but long-term exposure to high humidity suppresses the transpiration rate, which may lead to local calcium deficiency (Leech *et al*., 2002; Palencia *et al*., 2009; Akpenpuun *et al*., 2021a). Lieten (2002), Jayasekara *et al*. (2018), and Akpenpuun *et al*. (2021b) reported that a humidity range of 65% to 75% is required to achieve maximum yield. Conversely, reduced transpiration at night results in root pressure that improves calcium transport to the fruits.

There is continuous interaction between the microclimate conditions inside a greenhouse and the environmental conditions outside the greenhouse. The influence of one on the other and the general control of these conditions are determined by a particular greenhouse design: selection of shape, orientation, covering materials, number of spans, ventilation, installation of thermal, position of thermal screen when retracted in case of a moveable screen, and climate control system. The orientation and form of greenhouses, either single-span or multi-span, affect air temperature primarily because of solar radiation transmission and sun elevation; similarly, the number of spans impacts ventilation (von Elsner *et al*., 2000; Rabiu *et al*., 2022). Several studies have investigated the interrelationship of these variables on the microclimate of single-span greenhouses (Jayasekara *et al*., 2018; Rasheed *et al*., 2019b; Akpenpuun and Mijinyawa, 2020; Akpenpuun *et al*., 2021b; Ogunlowo *et al*., 2022). The present study investigates the relationship between the position of thermal screens on two single-span double-layer greenhouses (R-greenhouse and Q-greenhouse) and the greenhouse environment, fuel consumption, and strawberry yield. These findings highlight the best position of the thermal blanket for optimum solar radiation reception, which will subsequently affect the microclimate.

II. METHODOLOGY

A. *Description of Greenhouse for the Current Study*

The experiment was conducted in winter (November 2021–March 2022) at the Smart Agriculture Innovation centre, Kyungpook National University, Buk-gu, Daegu, South Korea. Daegu is a metropolitan city with a latitude of 35.60oN, a longitude of 128.35oE, and an altitude of 1100 masl. Daegu has a humid subtropical climate, and the average precipitation, relative humidity, daily photoperiod, the minimum and maximum temperature of 1131.5 mm, 61.6%, 6.2 hours, 10.1 °C, and 14.6 °C, respectively (Jayasekara et al., 2018; Akpenpuun et al., 2021b). Two single-span with an inner layer of polyethene and an outer layer of polyolefin greenhouses (double-layer greenhouses), namely R-greenhouse (RGH) and Q-greenhouse (QGH) were used. The dimensions of both greenhouses were 24 × 7 × 4 m with a 168 m2 floor area, and the side and ridge vents were 30% of the total floor surface. Both greenhouses had thermal screens installed between the inner layer of polyethene and the outer layer of polyolefins. Both greenhouses were oriented east-west to absorb the solar radiation best, and the structural shape and design were the same for both greenhouses (gothic roofed).

In contrast, the thermal screen was installed at the roof centre of RGH, while in QGH, the thermal screen was installed at 5° toward the north side of the greenhouse, as shown in Figures 1 and 2, respectively. The thermal screen properties were the thickness of 3.5 mm, thermal radiation transmittance of <0.001%, thermal conductivity of 0.037 W m −1 K −1, the reflectance of 0.10, and emittance of 0.90 for both greenhouses. The thermal screens were open during the day (08:30 h) and closed at night (18:00 h). To maintain the optimum temperature inside the greenhouse and supply sufficient carbon dioxide (CO2) for the crops, there were side walls that opened automatically when the greenhouse air temperature reached 21.5 °C. Figures 1 and 2 show that Roof vents were not used in this experiment; hence, the roof shape was insignificant. Four 0.5hp and 25 cm diameter window air circulating fans were mounted 1.9 m from the greenhouse floor at the east and west ends of each greenhouse, as shown in Figures 1 and 2. The greenhouse air temperature was maintained at these thresholds during winter using an adequate heating system as a boiler per greenhouse. The boiler's lower and upper-temperature limits were 7.5 °C and 8.5 °C for the activation and deactivation of the boiler, as Bradford *et al*. (2010) recommended a minimum temperature of 8 °C for strawberry growth and development. Diesel was used as the fuel for the boilers, and the daily fuel consumption was recorded using a digital flowmeter. Spiral heat dissipation pipes were installed beneath the greenhouse beds and connected to the boiler tanker to radiate heat energy as hot water flows through the pipe, raising the root zone and greenhouse air space temperatures.

Temperature, RH, and SR of the greenhouse air were measured continuously. 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 m/s; 30 s in stirred water, USA), resulting in 15 sensors per greenhouse. In addition, solar radiation sensors were placed at the top of the plant canopy to measure the SR, and three sensors were installed per greenhouse.

Seolhyang, one of the Korean local varieties of strawberry, was used as the study crop and cultivated on upstanding greenhouse beds, namely A, B, C, D, and E beds, which were 76 cm wide and 1500 cm long. The space between the crops and bed was 25 cm and 60 cm, respectively.

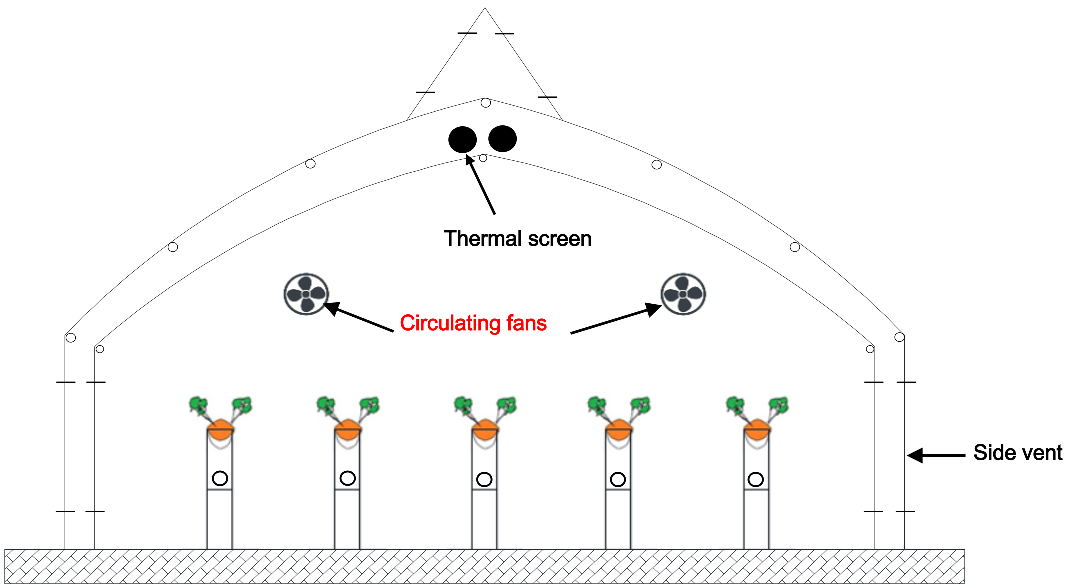

Figure 1: R-greenhouse with a thermal screen at the roof ridge.

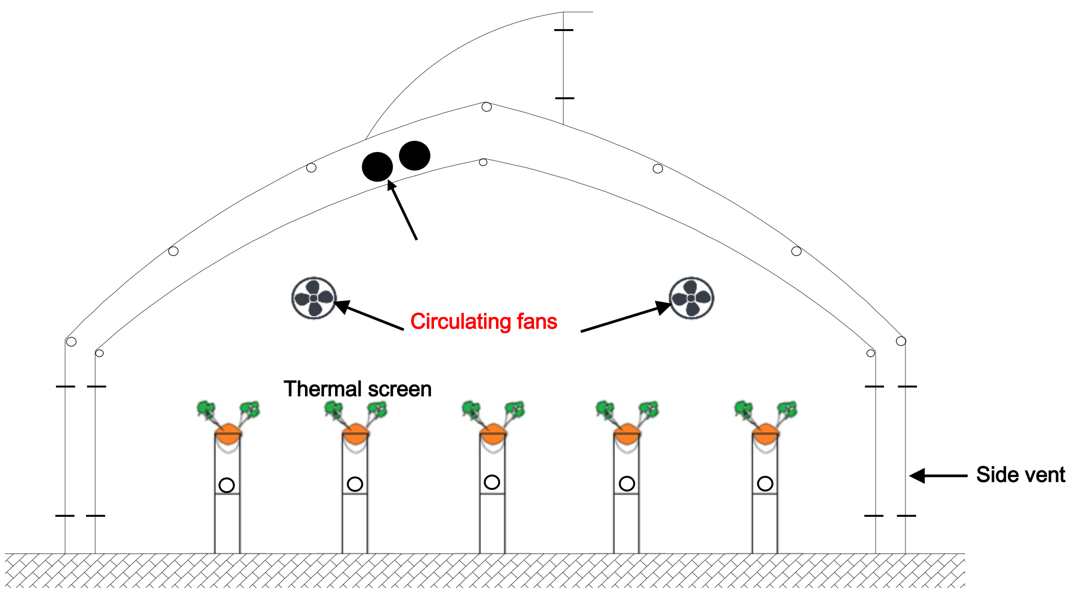

Figure 2: Q-greenhouse with a thermal screen on the north side of the greenhouse roof.

Tables 1- 3 and Figure 3 show the greenhouse parameters, experiment equipment and measured data, and inside view of both greenhouses with the thermal screen position, respectively.

Table 1: Greenhouse parameters.

Parameter	RGH	QGH
Span	Single	Single
Glazing type	PE (Double layer)	PE (Double Layer)
Dimension	24 x 7 x 4 m	24 x 7 x 4 m
Crop Type	Strawberry	Strawberry
Thermal screen position	Roof, centre	North side of the roof

Table 2: Experiment equipment.

Equipment	Purpose / Specification	Quantity
Boilers	To circulate the water	One per each GH, T=2
Fans	To aid air circulation inside the greenhouse	4 per each GH, T = 8
Sensors	HOBP pro-v2 onset	12 per greenhouse
Digital flowmeter	To measure daily fuel consumption	One per each GH, T=2
Digital Calliper	300 mm long	One set

GH = greenhouse, T = total

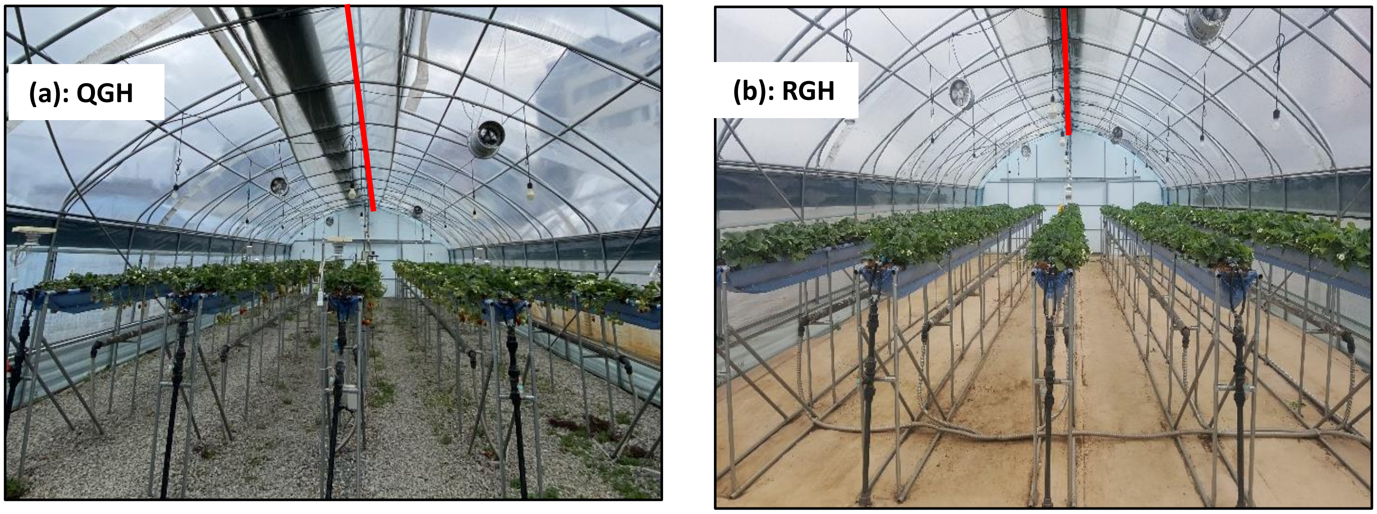

Figure 3. Inside view of both greenhouses with a thermal screen position.

Table 3. Measured data.

Measured data	Unit	Time interval	Sensor
Temperature	^0C	10 min	HOBP pro-v2 onset
Relative humidity	%	10 min	HOBP pro-v2 onset
Solar radiation	W/m^2	10 min	/
Vapour pressure deficit (VPD)	KPa	10 min	
Crop yield	Kg	Twice a week	/
Crop growth	mm	after 14 days	/
Fuel consumption	litre	every morning	/

The total number of crops per greenhouse was 624, with an average of 124 plants per bed. Plants in both greenhouses were irrigated and fertilised five times daily using the same open-loop drip irrigation setup. Fernandez *et al*. (2001) recommended cultivation procedures be followed. Irrigation started at 08:30 with an interval of 1 h 30 min, and each irrigation phase lasted for 2 min 30 s. For enhanced crop pollination, bumblebees (Bombus Terrestris L.) were introduced into both greenhouses at the flowering stage of the berry plants. The fruit began maturing in December 2021 and was continuously harvested twice a week until the completion of the experiment at the end of March 2022. The total yield per greenhouse was obtained by weighing the fruits per bed.

VPD was derived using the following equation proposed by (Akpenpuun *et al*., 2021a):

$$P_s = 610.78 \times \exp\left(\left(\frac{T}{T+238.3}\right) \times 17.27\right), \quad (1)$$

Where P_s is the saturation vapour pressure [Pa] and T is the temperature [°C].

$$\text{Vapour pressure deficit, (kPa)} = \frac{\left(1-\left(\frac{RH}{100}\right)\right)\times P_s}{1000} \quad (2)$$

Where VPD and P_s are measured in Pa, while the unit of measurement of relative humidity (RH) is the percentage.

B. *Data Collection and Analysis*

The greenhouse air temperature, relative humidity, and solar radiation were recorded at 10-minute intervals, and sensors (HOBP pro-v2 onset) were installed per bed in the front, middle, and end of the bed to record the microclimate data. Plant height, leaf length, width, and crown diameter were measured every 14 days. The collected data were subjected to descriptive and inferential statistical analyses at the significant level of 5% using Microsoft Excel (Microsoft Office 2021).

III. RESULTS AND DISCUSSION

A. *Microclimate Parameters*

The descriptive statistics report of the data recorded in greenhouses R and Q showed that the mean daily air temperature, RH, VPD, and solar radiation were 13.9±6.0 °C, 76.6±23.9%, 0.5±0.7 kPa, and 68.5±123.7 W/m2 in the RGH, respectively, and 14.1±5.7 °C, 75.7±22.3%, 0.5±0.7 kPa, and 72.8±132.7 W/m2 in the QGH, respectively. The total amount of solar radiation received by the RGH and QGH was 808247.2 and 858833.0 W/m2, respectively. The ranges of temperature, RH, VPD, and SR were 8.0 – 24.2 °C, 64.1 – 99.0%, 0.03 – 0.6 kPa, and 8.7 – 651.9 W/m2 in RGH, and 7.9 – 24.1 °C, 63.9 – 98.8%, 0.02 – 0.6 kPa, and 7.2 – 934.6 W/m2 in QGH respectively. Shamshiri et al. (2014) reported that while the temperature (T) and relative humidity (RH) of outside air were between 28 – 33 oC and 70 – 85%, the inside microclimate was between 68 – 70 oC and 20 – 35%, respectively, leading to an air vapour pressure deficit between 18 and 21 kPa in a single-span greenhouse covered with polyethene film. Such microclimate conditions correspond to a zero-growth response for tomatoes and subsequently eliminate any chances of successful production.

A one-way ANOVA test was performed to compare the means of the significantly different environmental parameters and fuel consumption presented in Table 4. The table shows no significant difference between air temperature, RH, VPD, and fuel consumption recorded in RGH and QGH. At the same time, there was a significant difference at $\alpha = 0.05$ probability level of significance of solar radiation recorded between RGH and QGH.

cultivation in air-inflated and conventional double-layer greenhouses reported by Jayasekara *et al.* (2018) and Sim *et al.* (2020). However, a conventional double-layer greenhouse's recorded greenhouse air temperature range was 11.8 – 24.7 °C. The mean temperature in this experiment was close to 13.0±2.3 °C, and 13.1±2.3°C reported by Akpenpuun *et al.* (2021b) in the polyolefin-thermal screens (PoTS) and polyolefin-thermal screens-polyethene (PoTSPe) covered greenhouses for strawberry. On average, the temperature is also within the range Kim (2010) reported for the day- and night-time temperatures of 15 – 25 ºC and 5 – 10 ºC, respectively. Although high temperatures benefit plant growth and yield, temperatures exceeding crop-specific ranges have adverse effects on plant growth and yield quality because high temperatures result in nutrient and hormone imbalances (Rouphaela *et al.*, 2018). Kittas *et al.* (2005), Katsoulas and Kittas (2008), Shamshiri *et al.* (2018), and Akpenpuun and Mijinyawa (2020) reported that plants exposed to high temperatures require high relative humidity to neutralise heat stress that results from high temperatures. Sønsteby *et al.* (2016) and Sim *et al.* (2020) noted that environmental fluctuations especially changes in temperature and light have a significant effect on the growth, development, and yield of strawberries. Both greenhouses were controlled and monitored throughout the experimental season to maintain the best temperature needed for successful strawberry production.

Table 4: One-way ANOVA, RGH and QGH environmental data.

Parameters	df	F statistics	p-value	F critical	Significant
QGHsr vs RGHsr	1	6.25	<0.05	3.84	Yes
QGHTemp vs RGHTemp	1	22.55	<0.05	3.84	Yes
QGHrh vs RGHrh	1	16.98	<0.05	3.84	Yes
QGHvpd vs RGHvpd	1	0.54	0.46	3.84	No
QGHfuel vs RGHfuel	1	0.06	0.81	3.89	No[1]

df = degree of freedom; QGH = Q-greenhouse; RGH = R-greenhouse; sr = solar radiation; rh = relative humidity; vpd = vapour pressure deficit; NS = not significant; significant level, p = 0.05

Figures 4, 5, and 6 present the air temperature, RH, and VPD trends in the RGH and QGH, respectively. Figure 4 shows that the maximum temperatures of 24.1 °C in the RGH and 24.2 °C in the QGH occurred on 01/12/2021. Later, the temperature dropped to approximately 12 °C and 13 °C before rising to 14.1 °C and 14.2 °C in the RGH and QGH, respectively, on 28 January 2022. Because of the variations in the ambient environment, which affect the indoor microclimate, as a result the greenhouse environmental parameters constantly fluctuated, most especially the greenhouse air temperature. On 28/02/2022, the temperature inside both greenhouses rose to 17 °C and 18 °C in RGH and QGH, respectively. Eventually, the temperature dropped to 13.5 °C in the RGH and 14.1 °C in the QGH at the end of the experiment. The minimum temperatures recorded in both greenhouses were 7.5 °C and 8.1 °C. Jones (2013) reported that optimal day- and night-time air temperature ranges of 21 - 29.5 °C and 18.5 – 21 °C are required for most greenhouse vegetables. The rise in temperature results in a decrement in crop growth and heat stress and causes ineffective transpiration (Gruda, 2005; Akpenpuun *et al.*, 2021b). The daytime air temperature in the RGH and QGH was maintained well within the daytime temperature range of 15 °C to 25 °C for strawberry

Figure 5 shows the results of recorded relative humidity; the patterns of RH fluctuation in the RGH and QGH are similar. The trend was the same for the outside RH, but the outside RH was lower than the RH inside the RGH and QGH. The maximum relative humidity was 99.0 and 98.9% in R- and Q-greenhouses, respectively, obtained on 17 December 2021. The minimum relative humidity was 64.1% on 19/12/2021 in the RGH and 63.9% on 17 December 2021 in the QGH. In December, the ambient RH was exceptionally low; at the same time, both greenhouses reached 99% RH at night, while in January 2022, the mean RH of RGH and QGH was approximately 65% during the day, when the outside relative humidity level was on average 40%.

RH is one of the most crucial climatic elements and impacts the water conditions of the greenhouse atmosphere and subsequently on all transpiration-related activities (Gruda, 2005). The relative humidity ranges recorded in the R- and Q-greenhouses were 64.1 - 99.0% and 63.9 - 98.9%, respectively. Lieten (2002) recommended an optimal range of 65–75% RH for good strawberry growth and yield during the day. The American Society of Agricultural Engineers (2003)

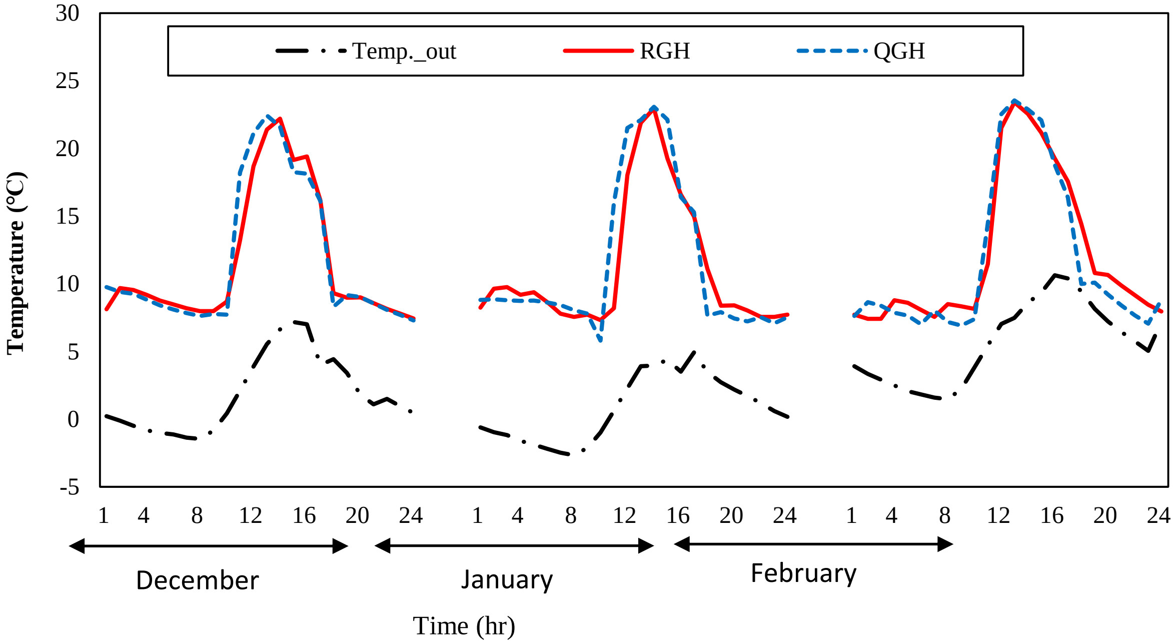

Figure 4: RGH vs QGH and their ambient temperature variations.

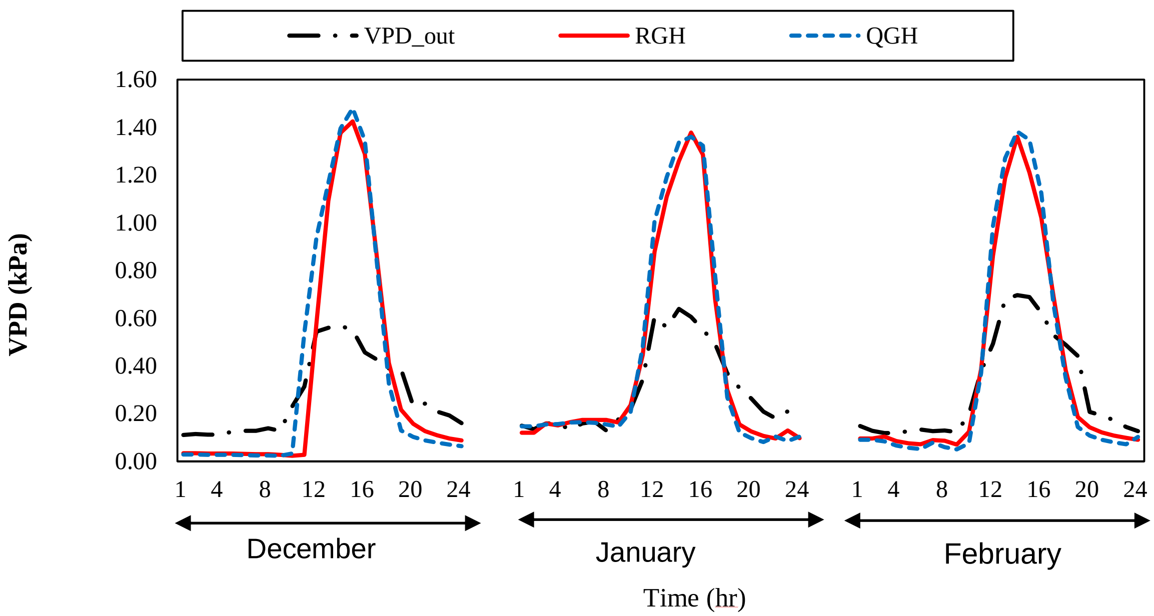

Figure 5: VPD variations in the RGH, QGH and ambient.

recommended relative humidity in the range of 60 – 90% as the most appropriate for greenhouse vegetables. Pollination has been reported to be either positively or negatively affected by atmospheric greenhouse RH. Harel *et al.* (2014) reported that pollination in greenhouses is significantly enhanced at 60% relative humidity. However, an excessive level of RH can lead to different plant diseases such as tip-burn and cat-facing in strawberries (Sim *et al.*, 2020; Akpenpuun *et al.*, 2021a). Jayasekara *et al.* (2018) recorded RH ranges of 50–100% and 40 – 85% in an air-inflated greenhouse and a conventional double-layer greenhouse, respectively.

Figure 6 shows a comparison of the VPD trends in both greenhouses and outside. At the beginning of the experiment, recorded VPD was 0.50 and 0.80 kPa in both the R- and Q- greenhouses. The minimum and maximum VPD values were 0.03 kPa and 1.42 kPa, and 0.02 kPa and 1.48 kPa in the R- and Q- greenhouses, respectively. The lowest VPD values of 0.03 kPa and 0.02 kPa in the R- and Q- greenhouses were recorded on 11 December 2021. During the night-time, the VPD recorded in both greenhouses ranged between 0.02 and 0.15 kPa, but this range went up to 0.40 and 1.48 kPa at daybreak on sunny days, respectively. Akpenpuun *et al.* (2021b), however, reported daily VPD ranges of 0.10 - 0.60 kPa and 0.03 - 0.50 kPa in a polyolefin-thermal screen (PoTS) and polyolefin-thermal screen polyethene (PoTSPe) greenhouses, respectively, whose position of the retracted thermal screen was at the roof ridge. A low VPD level during the day improves the yield of greenhouse vegetables. An extremely low VPD level, which indicates high RH in the greenhouse atmosphere, causes fungal disease, whereas a high

VPD can cause dehydration (Katsoulas and Kittas, 2008; Jayasekara *et al.*, 2018; Shamshiri *et al.*, 2018). Sim *et al.* (2020) and Akpenpuun *et al.* (2021a) reported a range of 0.10 to 0.45 kPa and 0.20 to 0.40 kPa in a conventional double-layer greenhouse and conventional single-layer and double-layer greenhouses, respectively, while Jayasekara *et al.* (2018) reported a VPD range of 0.03 - 0.20 kPa in an air-inflated double-layer greenhouse used for strawberry cultivation.

Because the greenhouses were adjacent, R-greenhouse cast a shadow on the south side of Q-greenhouse. However, the Q-greenhouse received more radiation at the centre and northside than the R-greenhouse. This resulted in the disparity in the total SR recorded in both greenhouses, where a total SR received by QGH was 858833.0 Wm^{-2} (229.4±120.5 Wm^{-2}), while RGH received a total SR of 808247.2 W/m^2 (229.3±130.9 W/m^2).

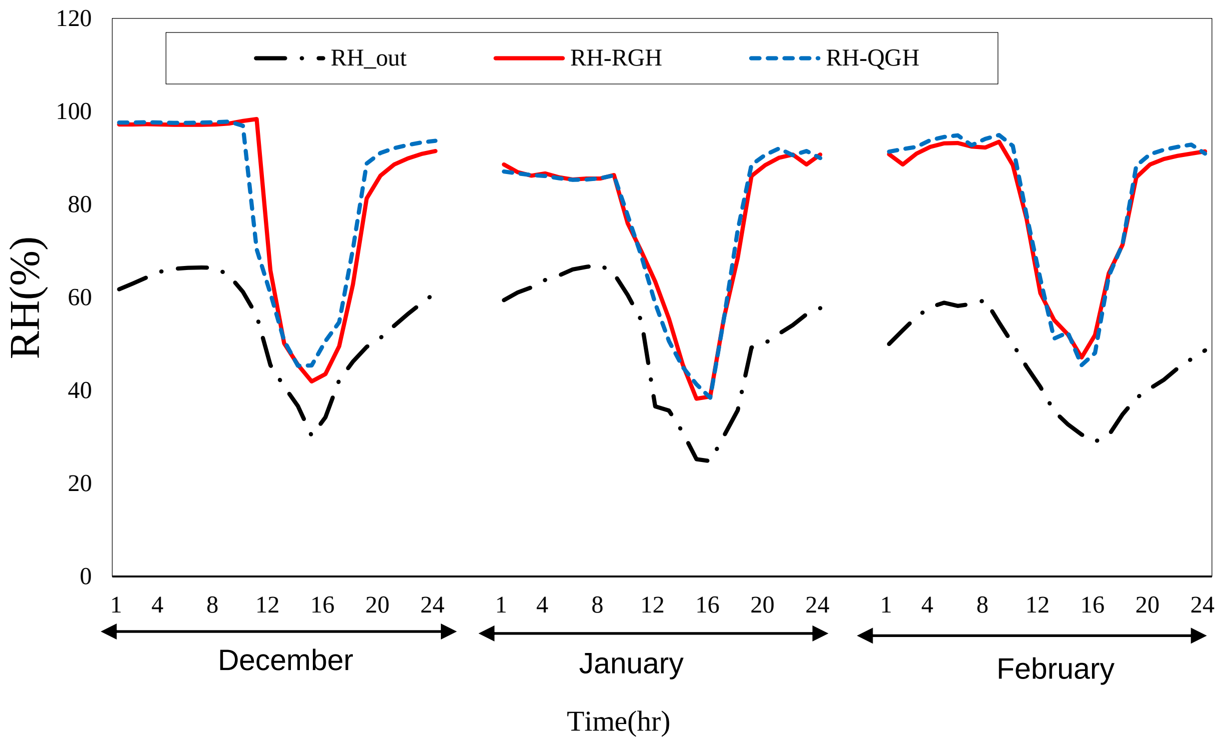

Figure 6: RH variations in the RGH, QGH and ambient.

For better comparison, solar radiation was studied at three separate locations in both greenhouses. Figures 7 and 8 show the comparison of solar radiation on the south, middle, and north side of the greenhouses. Figure 7 presents the solar radiation received in the R-greenhouse, and it shows that the southern part of the greenhouse received more solar radiation than all the locations where SR was recorded in the Q-greenhouse owing to obstacles such as the retracted thermal screen at the roof ridge which blocked the SR from reaching the Q-greenhouse. Figure 8 shows that the received SR in the QGH is the same in all three greenhouse locations. Figures 9, 10, and 11 show the SR distribution patterns in the RGH and QGH, their outdoor environments, and the total SR received by both greenhouses on a sunny day, respectively. Figure 9 shows that RGH obtains less SR on the north side compared to the south side and middle of the greenhouse; it is caused by the thermal screen shade, especially during mid-day. The reception of solar radiation by plants within the greenhouse environment varies. It depends on the atmosphere, nearby obstructions, shadows cast by nearby trees or structures, and greenhouse structural members. A clear atmosphere allows more photons to enter the greenhouse. The minimum and maximum solar radiation received in R- and Q- greenhouse was 7.2 - 834.6 Wm^{-2} and 8.7 - 651.9 Wm^{-2}, respectively.

In addition, the Q-greenhouse's retractable position of the thermal screen was on the north and south sides of the greenhouse, which is the reason for the high value of received SR, as there was no obstruction at the roof ridge, unlike the R-greenhouse, whose position of the retractable thermal screen was at the roof ridge. Akpenpuun *et al.* (2021a) reported maximum SR values of 549.83 Wm^{-2} and 631.6 Wm^{-2} for the single-layer single-span greenhouse (SLGH) and double-layer single-span greenhouse (DLGH), respectively, whose thermal screens rolled up to the roof ridge. Kim (2010) investigated short-day strawberry species and reported that SR in the range of 16.4 to 91.6 Wm^{-2} is sufficient for short-day this kind of strawberry cultivars. According to a report by Kim (2010), the SR values received in both greenhouses are sufficient to sustain strawberry production of any kind. Faust *et al.* (2005) reported solar radiation values of 18.9 to 37.9 Wm^{-2}, 37.9 to 75.7 Wm^{-2}, 75.7 to 113.5 Wm$^{-2,}$ and >113.5 Wm^{-2} for low–, medium–, high– and extremely high- light crops, respectively. In the same context, Mellalou *et al.* (2021) reported that since strawberry is a very high light-requiring crop, 151.4 Wm^{-2} of SR received for 12 to 16 hours per day is sufficient for its successful production. As much as SR is essential for crop growth and development, excess SR can increase greenhouse air temperature by approximately 20 °C to 30 °C higher than

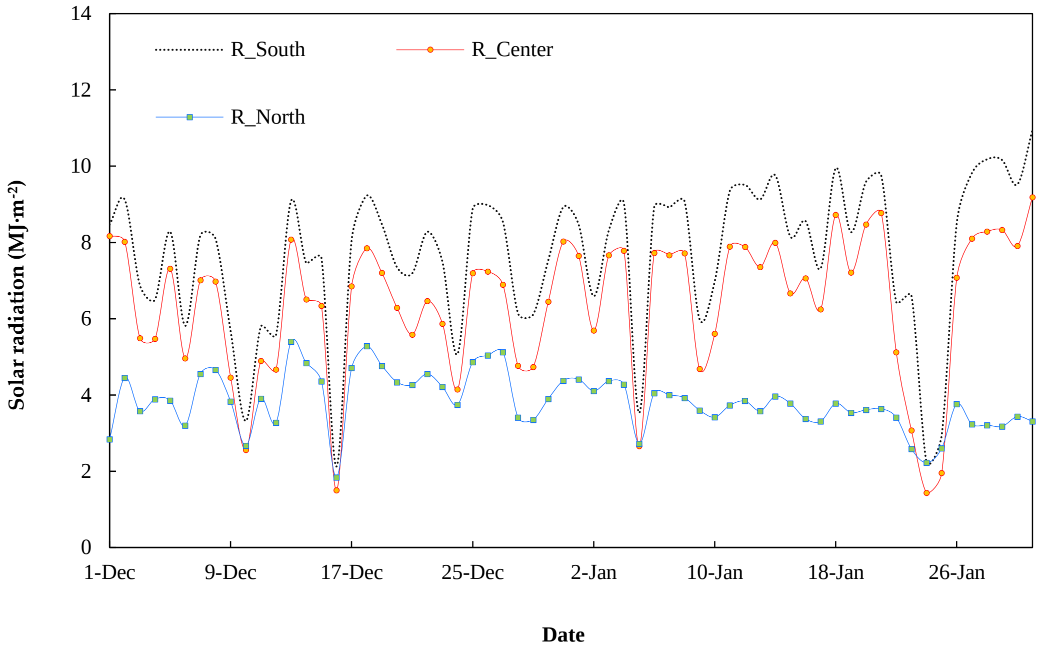

Figure 7: A pattern of solar radiation inside R-greenhouse.

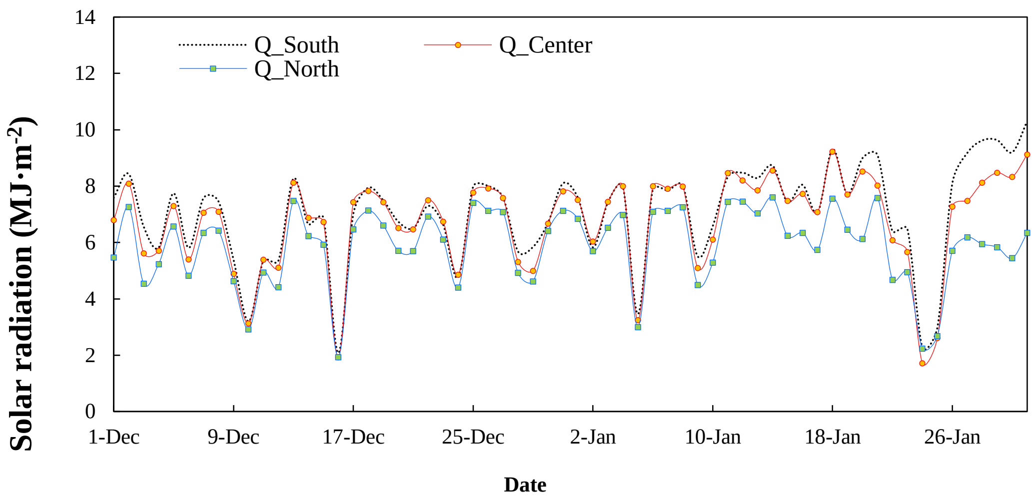

Figure 8: The pattern of solar radiation inside Q-greenhouse.

the ambient air temperature (Kittas *et al.*, 2005; Shamshiri, 2017). Furthermore, prolonged exposure to high air temperatures beyond the temperature tolerance level of plants limits evapotranspiration, thereby leading to fruit abortion and flaccid leaves as a result of drawing inadequate water through the root system (Adams, 2002; Shamshiri, 2017).

One-way ANOVA statistical tests were conducted on the growth data of both greenhouses to determine whether there was a significant difference between growth parameters. The growth parameter data for both greenhouses are presented in Table 5. Table 5 shows a significant difference between the growth parameters of RGH and QGH. A post hoc test was performed on the growth data to find out where the differences resulted from the ANOVA test. Based on the post hoc test results, the differences occurred between (LL) on row A and between (LW) on rows A and B. Also, crop height was significantly different in rows A, B, and C, while the crown diameter was remarkably different in row A. Meanwhile, the post hoc test results also indicate that row B in the QGH had more significant LL, LW, and CH, while LW, CH, and CD had higher values in the RGH in row A. Notably good vegetative growth does not translate to an abundant yield.

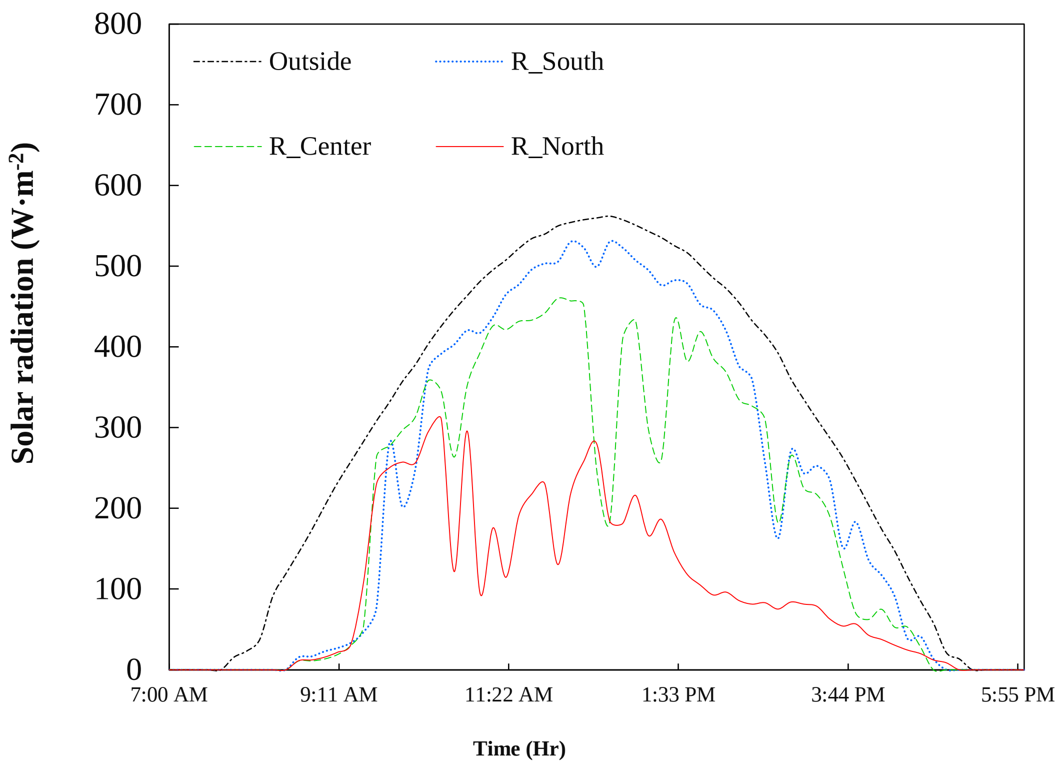

Figure 9: The trend of daily solar radiation inside vs. ambient, of R-greenhouse.

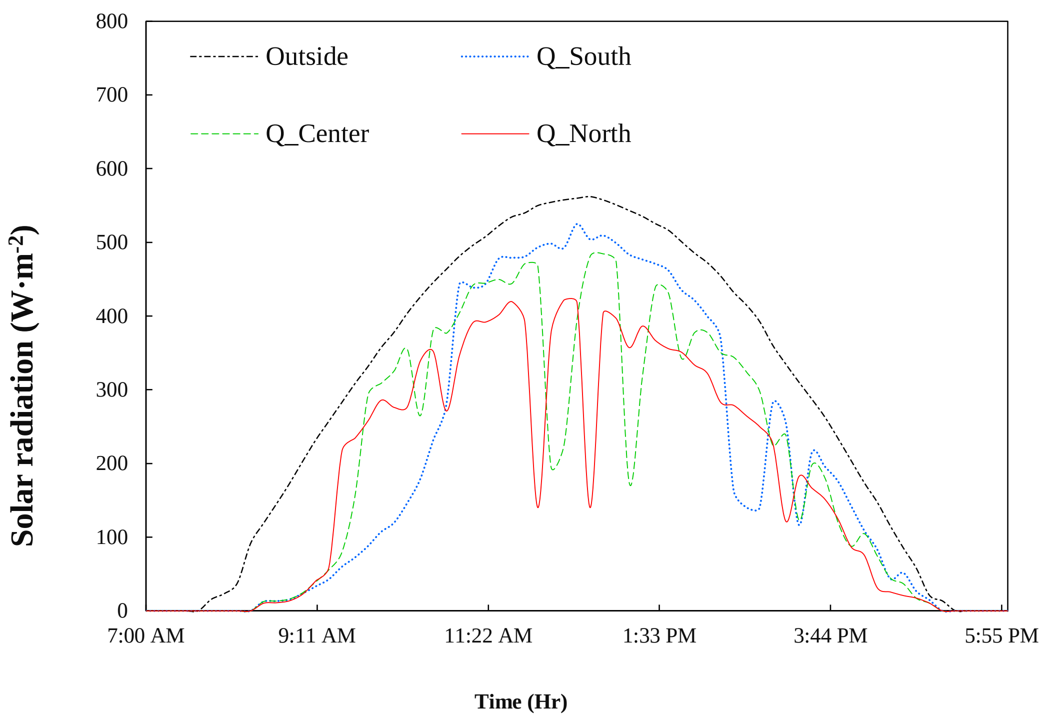

Figure 10: The trend of daily solar radiation inside vs. ambient of Q-greenhouse.

B. Fuel Consumption

Figure 12 shows the fuel consumption from December to March in RGH and QGH. The descriptive statistics of the diesel consumption throughout the experiment showed that the mean daily diesel consumption was 3.1±2.6L and 3.2±2.8 L for RGH and QGH, respectively. Usually, thermal screens are used to shield a greenhouse at night to conserve energy in cold climates. Accordingly, the adoption of thermal screens was to aid in energy conservation in this experiment. The heating system used to heat the greenhouse atmosphere on cold days and nights was activated on 19/12/2022 and worked till 25/03/2022 when the ambient temperature was no longer below the greenhouse temperature. In total, both greenhouses consumed 643.99 litres of fuel in the mentioned interval of

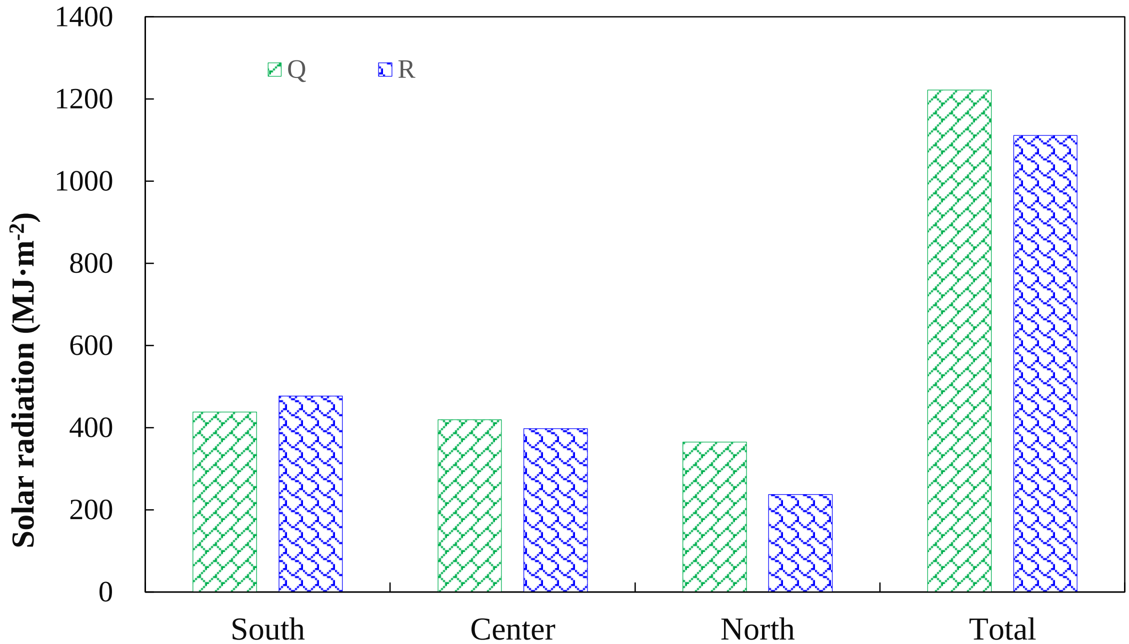

Figure 11: Total solar radiation received by R and Q greenhouses at the south, centre, and north side.

Table 5: Analysis of variance of RGH and QGH strawberry growth data.

Parameter		Sum of squares	df	Mean square	Fstatictics	p-value	F critical	Significant
LL	Between Groups	21477.60	2	10738.80	792.84	<0.01	0.16	yes
	Within Groups	162.54	12	13.55				
	Total	21640.14	14					
LW	Between Groups	15428.46	2	7714.23	650.08	<0.01	0.16	yes
	Within Groups	142.40	12	11.87				
	Total	15570.86	14					
CH	Between Groups	63686.41	2	31843.20	71.48	<0.01	0.16	yes
	Within Groups	5345.69	12	445.47				
	Total	69032.10	14					
CD	Between groups	977.69	2	488.85	32.46	<0.01	6.39	yes
	Within Groups	180.72	12	15.06				
	Total	1158.41	14					

LL, leaf length; LW, leaf width; CH, crop height; CD, crown diameter; df, degree of freedom

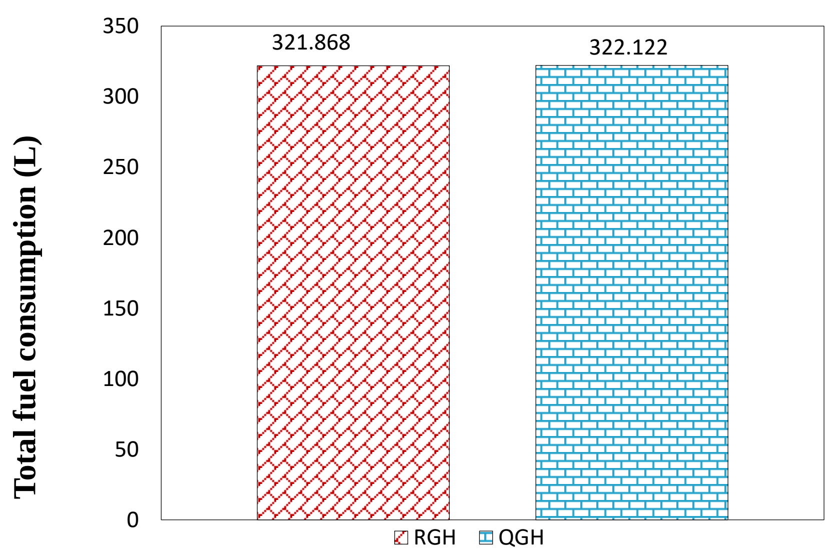

Figure 12: The total fuel consumption by both greenhouses.

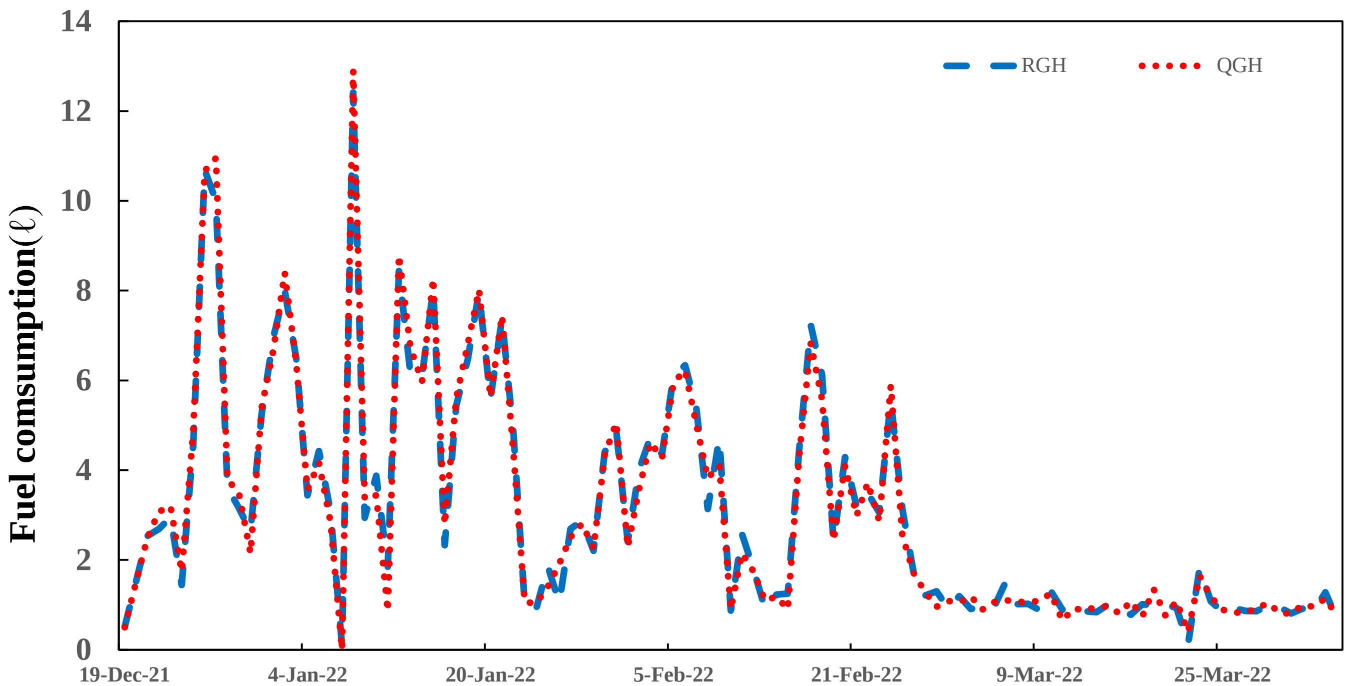

Figure 13: A trend of daily fuel consumption by both greenhouses. **Date**

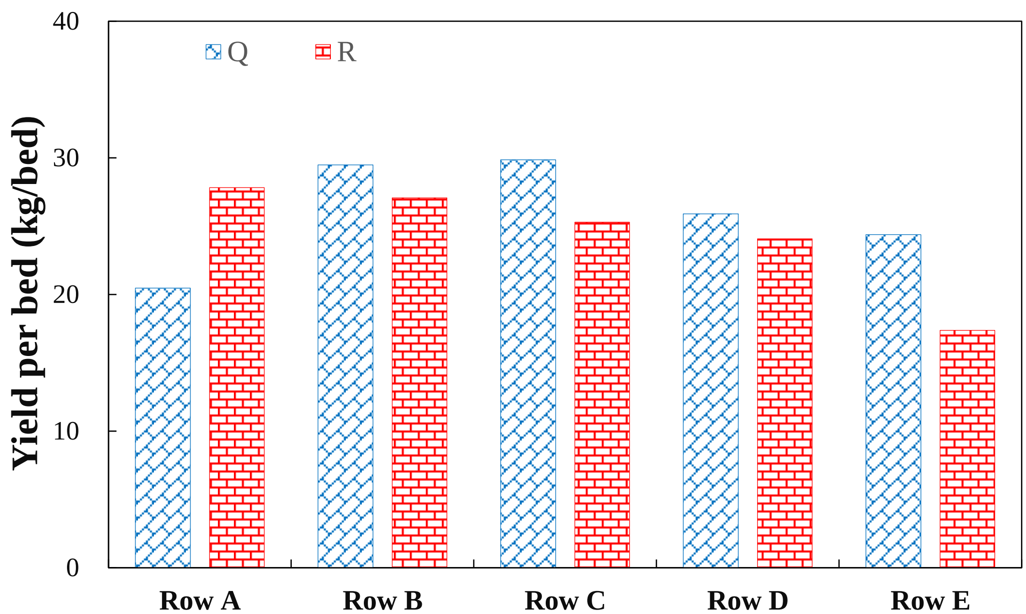

Figure 14: Total yield per bed of both greenhouses.

boilers. This total fuel usage is less than the total of 794.6 L consumed by PoTS (5.5±3.9 L) and PoTSPe (3.5±2.5 L) greenhouses, as reported by Akpenpuun et al. (2021b).

Furthermore, the fuel consumed in this experiment is much lower than a total of 1101.5 litres in conventional double-layer and air-inflated double-layer greenhouses, as Jayasekara et al. (2018). Figure 13 shows the daily fuel consumption by both greenhouses. The fuel consumption range was higher in January in both greenhouses, as RGH consumed 144.172 litres and QGH consumed 145.358 litres. Therefore, in terms of fuel consumption and energy savings, both greenhouses performed coequal.

C. *Yield*

The total marketable yield was weighed and calculated per bed of both greenhouses per month and the total yield per greenhouse to determine if the position of the thermal screen affected the yield. Figure 14 shows the yield per bed for both the RGH and QGH. Except for the yield obtained from bed A, where RGH had a higher yield than QGH, beds B, C, D, and E each yielded more in QGH than in RGH. Sim *et al.* (2020), who studied the correlation of strawberry yield with temperature, VPD, RH, and photosynthetic active radiation (PAR), concluded that SR was positively correlated with early and late strawberry growth stages and fruit yield. This explains why QGH yielded more strawberry fruit than RGH. Additionally, from the current experiment, Figure 11 shows that the south side of RGH received more SR than the QGH, but the QGH received more SR at the centre and on the north side. The beds in the QGH which received more SR had a higher yield. Furthermore, Figure 15 presents the total yield per month which proves that the QGH had a better yield in December, January, and February. Figure 16 shows the total yield per greenhouse, where QGH yielded 227.875 kg, and RGH yielded 186.449 kg. The summation of the yield in both greenhouses was 414.3 kg, while the total yield in the PoTS and PoTSPe greenhouses, whose position of the thermal screen was at the roof ridge, as reported by Akpenpuun *et al.* (2021b) was 171 kg. Jayasekara *et al.* (2018) reported a total yield of 282 kg in a conventional double-layer greenhouse and an air-inflated double-layer greenhouse.

IV. CONCLUSION

This study investigated the impact of the position of thermal screens on the environmental parameters, crop parameters and fuel consumption of two single-span greenhouses. The environmental parameters measured were temperature, RH, VPD and SR, while the crop parameters were growth and yield. It can be concluded from the results obtained that there was no significant difference in the ranges of air temperature, relative humidity, and VPD recorded in both greenhouses and the QGH, whose thermal screen was angled toward the north side of the greenhouse, received more solar radiation than the RGH, whose thermal screen was at the roof ridge. Also statistically insignificant was the total heating energy consumed by both greenhouses (QGH and RGH). However, the growth data showed a significant difference between the growth parameters in both greenhouses with QGH having higher growth parameter values and consequently having higher yields.

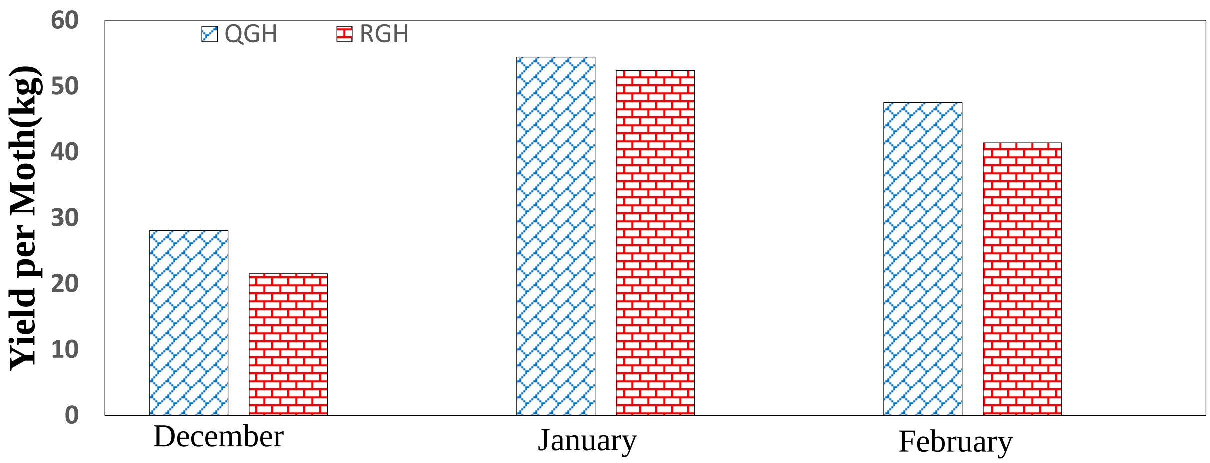

Figure 15: Total yield per month.

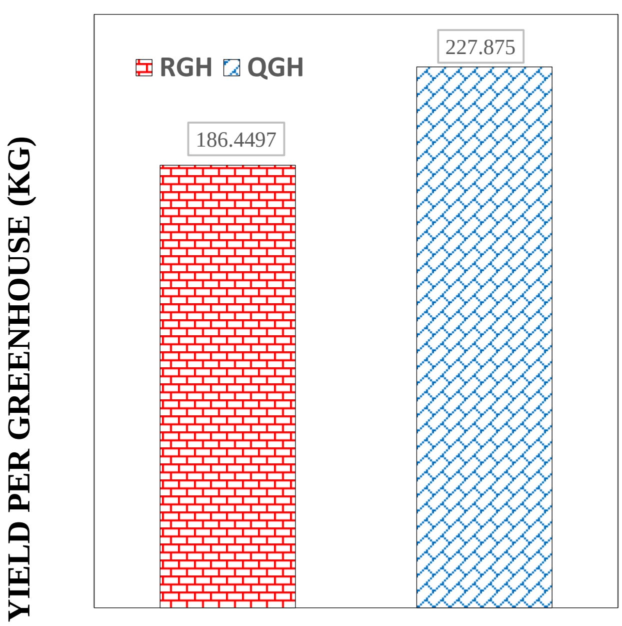

Figure 16: Total yield per greenhouse.

This study has shown that installing a thermal screen at 5° from the eave on the north side of the greenhouse resulted in the QGH being effective in terms of solar radiation reception and higher yield. However, growers can select the proposed thermal screen position based on the output.

AUTHOR CONTRIBUTIONS

Conceptualisation, **H.W.L., W.H.N., Q.O.O.** and **H.T.K.**; methodology, **H.W.L., W.H.N., T.D.A., Q.O.O., E.Z., M.A.A.** and **A.R.**; formal analysis, **E. Z.** and **T.D.A.**; investigation, **E.Z., Q.O.O., W.H.N., O.S.A., M.A.A.** and **A.R.**; resources, **H.W.L.**; data curation, **E.Z., T.D.A., Q.O.O., W.H.N.** and **O.S.A.**; writing—original draft preparation, **E.Z.**; writing— review and editing, **T.D.A., H.T.K.** and **H.W.L.**; visualisation, **E.Z., Q.O.O., W.H.N.** and **T.D.A.**; 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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