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Maximising Strawberry Yield in Single-Layered and Double-Layered Gothic Greenhouses: A Microclimate Approach

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ABSTRACT: Seolhyang variety of strawberry was grown in two gothic greenhouses with one layer and two layers of glazing material and a layer of shading screen. The objective of the study was to optimise strawberry yield using temperature, relative humidity (RH), vapour pressure deficit (VPD), and solar radiation (SR) in a single-layered (1Lgh) and double-layered (2Lgh) single-span gothic greenhouse. Greenhouse climate data were recorded using standard data loggers and sensors. The data were analysed using descriptive and inferential analysis. During the day, significant differences were observed between the 1Lgh and 2Lgh in terms of VPD and SR, while during the night, significant differences were found in RH and VPD ($p<0.01$). The yield in the 1Lgh was 3.2% higher than in the 2Lgh, the higher daytime VPD and lower nighttime RH in the 1Lgh may possibly explain this observation. The environmental parameters had significant interaction on yield with resultant R^2 values of 0.80 and 0.50 for 1Lgh and 2Lgh, respectively.

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A structure glazed with glass or plastic, known as a greenhouse, is used for crop production in a controlled environment. The primary goal of a greenhouse is to regulate temperature, relative humidity, vapour pressure deficit, and light to create ideal conditions for crop growth. Greenhouses guarantee food safety, prolong the growing season, and facilitate year-round crop production through the implementation of biosecurity measures (Akpenpuun and Mijinyawa, 2018; Akpenpuun et al., 2022). Frantz et al. (2004) suggested that by regulating the root- and aerial-environment, it is possible to achieve rapid growth and productivity in a controlled setting. A strawberry is a small, sweet, and fragrant fruit that belongs to the genus Fragaria in the rose family. Strawberry has a short flowering period of 35 to 40 days and a short maturity period of 20-40 days after fertilization. It is known for its bright red colour, juicy flesh, and characteristic seeds that dot its surface. The strawberry plant is a perennial herbaceous plant that produces

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fruit, which is typically consumed fresh or used as an ingredient in various culinary preparations, such as desserts, jams, and beverages. Strawberries are rich in vitamins, minerals, and antioxidants, making them a popular choice for a healthy and delicious snack (Li et al., 2010; Khalid et al., 2013). To meet market demands and labour availability, a wide range of different production systems are utilized for growing strawberries, aiming to achieve high yields of quality fruit while maintaining flexibility (Jayasekara et al., 2018). There are two methods for growing strawberries: one is in the open field using the hill- and matted-row system and the other is under protection on benches. Mulching either straw or plastic serves multiple purposes, including aiding in weed control, maintaining soil moisture, regulating soil temperature, protecting roots from cold damage, minimizing fruit decay, conserving irrigation water, and reducing contamination by keeping the fruit elevated above the soil surface (Moretti et al., 2010). Optimum growth, development, and yield in terms of quality and quantity require day and night time air temperature ranges of 18-24 ºC and 10-13 ºC, respectively. Similarly, for the transportation of nutrients and effective metabolic activities, air relative humidity and daily light integral (DLI) range of 60-75% and 17-20 mol m^{-2} d^{-1}, respectively, are necessary. The literature lacks sufficient studies on the interactions of environmental parameters on strawberry productivity. Nevertheless, researchers such as Khalid et al. (2013) and Palencia et al. (2009) have explored the relationship between RH and the performance of greenhouse-grown strawberry, the effects of organic amendments on vegetative growth, fruit quality, and yield efficiency of strawberry, and the correlation between strawberry yield and temperature and solar radiation, respectively.

Other researchers have also examined the influence of humidity on vegetables and ornamental plants, noting that high humidity promotes vegetable growth, while prolonged suppression of transpiration due to high humidity can cause local calcium deficiency (Palencia et al., 2009). Lieten (2002) and Jayasekara et al. (2018) studied the impact of relative humidity on strawberries in the greenhouse and reported that a humidity range of 65 to 75% is necessary to achieve maximum yield. However, these studies overlooked the combined interaction of environmental parameters like solar radiation, temperature, RH, and VPD on strawberry yield. Therefore, the objective of the study was to maximise the strawberry yield using temperature, relative humidity (RH), vapour pressure deficit (VPD) and solar radiation (SR) in single-layered and double-layered gothic greenhouses.

MATERIALS AND METHODS

The gothic greenhouses utilized in this experiment were situated at the Smart Agricultural Innovation Centre, Kyungpook National University, Buk-gu, Daegu, South Korea. They were positioned in the East-West direction, as this orientation is ideal for maximising solar radiation reception in the study area, particularly during the winter months when ambient temperatures are extremely low (Sethi, 2009). The greenhouses had identical structural configurations (22 m in length, 8.4 m in width, and 4 m in height), but had different roof vents configurations, however, one side of the 2Lgh was permanently closed during this experiment, thereby, making them similar in shape. The greenhouses, however, differed in the number of layers of covering materials. One of the greenhouses, referred to as 1Lgh, was covered with a single layer of polyolefin and a layer of thermal screen, while the second greenhouse, known as 2Lgh, had two layers of polyolefin and a layer of thermal screen. The physical and light properties of polyolefin and thermal screen are presented in Table 1.

Table 1. Polyolefin and thermal screen properties

S/No.	Property	Polyolefin	Thermal screen
1	thickness	200 µm	3.5 mm
2	transmittance	91%	<0.001
3	Conductivity	-	0.037 $Wm^{-1}K^{-1}$
4	Reflectance	-	0.10
5	Emittance	-	0.90

The operation of the roof and side vents was determined by the set point temperatures of 21°C and 23°C, respectively, falling within the optimal air temperature range of 18°C to 24°C for the growth and development of greenhouse crops. The greenhouses were naturally ventilated and to facilitate ventilation and air movement within the microclimate, four 0.5 hp air-circulating fans were installed per greenhouse. Since the experiments took place during the winter season, the air temperatures in the greenhouses were expected to be lower than the optimal range for strawberries. Therefore, heating systems (boilers) were installed in each greenhouse to maintain the air temperature within the lower limits of 8 °C-10 °C. The boilers were programmed to activate the heating of the greenhouses air space when the temperatures dropped below 7.5 °C (<8 °C) and deactivate once the air temperatures in the greenhouses reached 8.5°C (>8.0°C). The Seolhyang variety of strawberry was transplanted on October 3, 2020. It was planted on five benches in each greenhouse, which were spaced 60 cm apart from center to center and measured 76 by 1500 cm. The plants on each bench were placed 25 cm apart, resulting in a plant density of 132 per bed and a total of 660 plants per greenhouse.

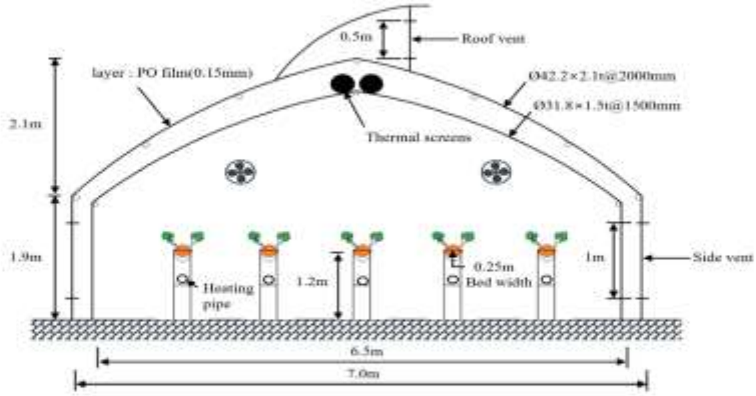


Fig 1. One Layer greenhouse

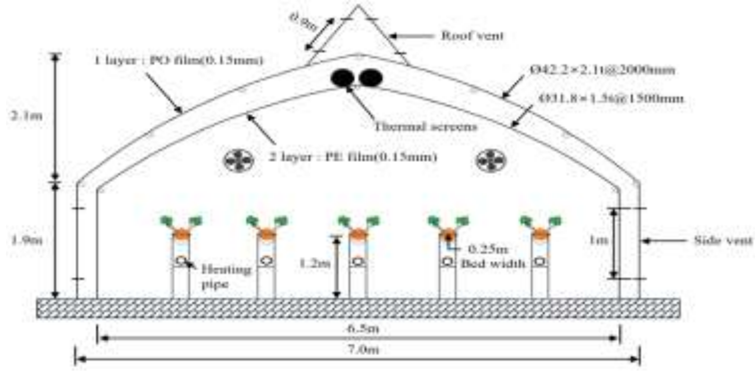
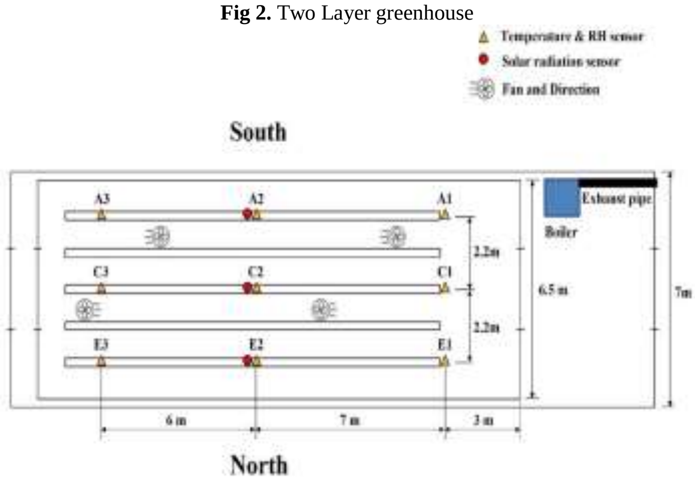


Fig 2. Two Layer greenhouse



Fige3. Sensors, fans and boiler positions

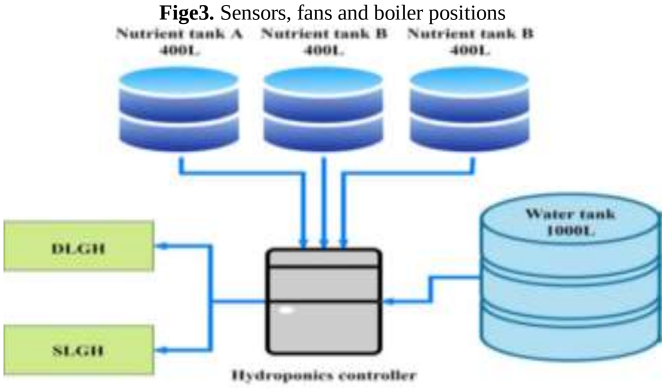


Fig 4. Irrigation and nutrient systems

The benches were aligned along the length of the greenhouse structure. For irrigation, the greenhouses were supplied with nutrient solutions five times a day using an open-loop drip fertigation system. The irrigation sessions occurred at intervals of 1 hour and 30 minutes, starting from 8:30 am. Each irrigation period lasted for 3 minutes. Strawberry standard cultivating practices adopted by Fernandez et al. (2001) were followed. Continuous measurements were taken for greenhouse air temperature, RH, and SR.

A total nine Thermohygrometer (accuracy: ±0.25°C, HOBO PRO v2 U23 Pro v2, ONSET, USA) were mounted on three benches out of the five benches in the greenhouse at 1.40 m above the greenhouse floor and 50 cm apart, while three SR sensors (accuracy: ±8 in 0° to 40°C and ±30 in -40° to 60°C, HOBO RX3000, ONSET, USA) were mounted only on the outer and centre benches in each greenhouse. All measurements were taken at an interval of 10 minutes totaling 5 readings in 1 hour. The determination of vapour pressure deficit (VPD) followed the method described by Noh and Lee (2022) as shown in equations 1, 2 and 3.

$$SVP = 0.6108 \exp\left(\frac{17.27T}{T+237.3}\right) \quad 1$$

$$AVP = SVP\left(\frac{RH}{100}\right) \quad 2$$

$$VPD = SVP\text{-}AVP \quad 3$$

Where, AVP = actual vapour pressure; SVP = saturated vapour pressure; RH = relative humidity; T = air temperature

Harvested berry fruits from each greenhouse were weighed using a digital weighing balance to assess the yield per bench and total yield per greenhouse. The collected data were categorized into daytime (07:10 to 18:50) and nighttime (19:00 to 07:00).

Subsequently, descriptive and inferential statistical techniques (analysis of variance and regression analysis) were employed to ascertain the relationship between yield and environmental parameters. Figures 1, 2, 3 and 4 show the one-layer greenhouse (1Lgh), two-layers greenhouse (2Lgh), sensors, fans and boiler positions, and irrigation and nutrient systems, in that order.

RESULTS AND DISCUSSION

The descriptive statistics showed that the mean day- and night- time temperature of the 1Lgh was 15.7±2.5 ^{o}C and 10.2±2.3 ^{o}C, respectively, while 15.9±2.5 ^{o}C and 10.3±2.7 ^{o}C were achieved in the day and night, respectively, in the 2Lgh. The minimum and maximum daytime temperature recorded in 1Lgh was 9.3 ^{o}C and 21.8 ^{o}C, which were similar to 9.2 ^{o}C and 21.7 ^{o}C recorded in the 2Lgh. Likewise, the nighttime minimum and maximum temperatures achieved in the 1Lgh and 2Lgh were 8.1 and 19.6 ^{o}C, and 7.9 and 19.3 ^{o}C, respectively. These readings are similar to the report by Khammayom et al. (2022), who recorded daytime temperatures to vary between 23 °C and 28 °C whereas nighttime temperatures varied between 5 °C and 10 °C. The difference between the mean of daytime and nighttime temperatures between the greenhouses was approximately 0.2 °C. Tekai (2010) recommended daytime temperatures of 23 °C to 28 °C and nighttime temperatures of 5-10 °C, while Khammayom et al. (2022) recorded mean greenhouse air temperatures of approximately 17.8 °C and 5.8 °C during the day and night, respectively. Although high temperatures can be beneficial for plant growth and yield, however, exceeding the specific temperature ranges can have negative effects, such as nutrient and hormone imbalances (Rouphaela et al., 2018; Khammayom et al., 2022) (. Furthermore, there were no significant differences observed between the day and night temperatures of the 1Lgh and 2Lghat a significance level (α) of 0.05.

The daytime RH range was 46.6%-91.7% and 46.6%-93.5% 1Lgh and 2Lgh, respectively, whereas the night-time range was 68.5%-95.7% and 79.5%-98.6% in the 1Lgh and 2Lgh, in that order. The mean daytime RH in the 1Lgh and 2Lgh was 63.1±10.1% and 66.1±10.3%, respectively. The mean RH difference between the 1Lgh and 2Lgh in the daytime and nighttime was approximately 3%. The humidity ranges in the 1Lgh and 2Lgh are in line with the recommendation of the American Society of Agricultural Engineers (2003) standards that recommend RH in the range of 60%-90% as the most appropriate for greenhouse vegetables. Khammayom et al. (2022) reported 30% to 92% in their experiment, while Lieten (2002) recorded RH variability of 65% to 75% during the day for optimum strawberry yield in the greenhouse. An RH level lower than the optimum will result in reduced fruit weight and yield, while a higher humidity level will stimulate vegetative development, but reduce fruit firmness, and shelf life and also promotes the accelerated development of fungal diseases. The day- and night- time mean VPD was 0.2 and 0.8 kPa, respectively, under the 1Lgh, while in the 2Lgh day- and night- time mean VPD was 0.1 and 0.8 kPa, respectively. The daytime vapour pressure deficit in both greenhouses was lower than the ranges reported by Shamshiri and Ismail (2013) which was 0.8 to 0.95 kPa. VPD in the range of 0.5 to 0.8 kPa and 0.3 to 1.0 kPa are ideal for greenhouse vegetables (such as tomato, sweet pepper and eggplant) and horticultural crops (Bakker, 1991; Iraqi et al., 1995) VPD beyond 1 kPa leads to stress, while 1.5 to 2 kPa reduces stomatal conductance. López-Morales et al. (2008) and Amani et al. (2020) also recommended that the optimal VPD range is 0.45 to 1.25 kPa for most greenhouse crops with 0.8 to 0.9 kPa being the most appropriate. The descriptive statistics of the solar radiation (SR) received in the 1Lgh and 2Lgh show that the mean SR received by the 1Lgh was 151.9±101.8 Wm^{-2}, while 2Lgh received 160.9±111.5 Wm^{-2}. Yoshida et al. (2016) reported that though strawberry requires high light intensity, strawberry does relatively well in light intensity range as low as 32.7-98.1 Wm^{-2}. The daylight integral (DLI), however, achieved in the 1Lgh and 2Lgh was greater than the lowest range of light intensity recommended by Yoshida et al. (2016). Hidaka *et al.* (2013) recorded that SR in the ranges of 45.4-71.9 Wm^{-2} and 75.7-95.6 Wm^{-2} are the minimum SR levels for greenhouse crops, while Faust et al. (2005) reported recommended SR in the range 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 light, medium light, high light and very high light greenhouse crops. Solar radiation achieved in 1Lgh and 2Lgh was significantly different ($p \leq 0.05$). This was due to the higher angle of incidence of the sun's rays both in the morning (sunrise in the east), in the afternoon (sunset in the west) and the vertical rays at noon. 2Lgh

The monthly yield obtained in 1Lgh and 2Lgh is presented in Figure 4. The 1Lgh had the highest yields of 45 kg and 13 kg in February and March 2021, while 2Lgh had the highest yield of 5 kg in December 2020 and 30 kg in January 2021. The mean yield of 1Lgh and 2Lgh was 21.7±19.0 kg and 21.0±15.6 kg, respectively. The total yield obtained 1Lgh (87 kg) was higher than the yield obtained in 2Lgh (84 kg) by 3.2 %. The analysis of variance (ANOVA) result ($F_{(1,6)} = 5.99$) of yield was statistically insignificant at $\alpha = 0.01$ levels of significance.

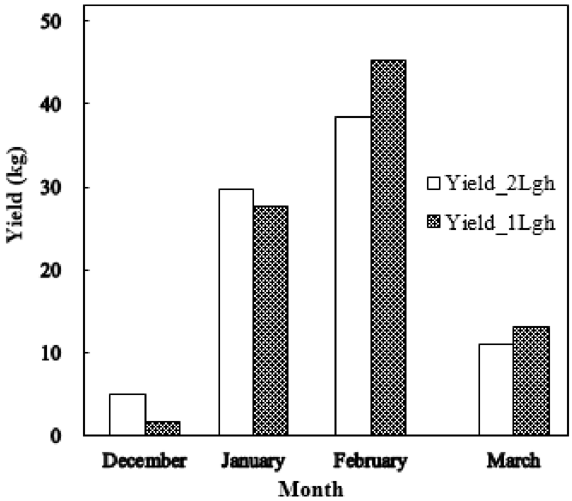


Fig 4. Monthly berry yield.

The regression analysis was carried out using STATA/SE, version 14.2. The model for yield prediction was defined based on the significant level of the model (best-fitted model), the significance level of the environmental parameters and the coefficient of determination (R^2), as a model with a high R^2 value better describes the relationship between the parameters under investigation. Linear regression analysis was used to establish the relationship between the air temperature, RH, VPD and SR on strawberry yield obtained in 1Lgh and 2Lgh. The analysis showed that the combined effect of air temperature, RH, VPD and SR on the yield in 1Lgh was statistically significant at a 5 % level of significance (F (4, 21) = 18.22; Prob>F = 0.0000). However, temperature (p = 0.05) and solar radiation (p<0.01) had a significant effect but an inverse relationship on yield with coefficients of regression values of -74.07 and -4.59, respectively. RH (p = 0.47) and VPD (p = 0.33) had insignificant individual effects on yield, but a positive relationship with yield with coefficients of regression values of 17.77 and 1052.42, respectively. The coefficient of determination (R^2) and adjusted coefficient of determination (Adj R^2) of 0.78 and 0.73 were obtained. The values of R-squared show 78 % of the variation in strawberry yield in 1Lgh can be explained by air temperature, RH, VPD and SR jointly. Equation 1 is for yield prediction in 1Lgh.

$$Y_{1Lgh} = 4225.33 - 74.07T + 17.77RH + 1052.42VPD - 4.59SR$$

The regression analysis on data obtained in 2Lgh showed that the overall effect of environmental parameters (air temperature, RH, VPD and SR) have a significant effect on yield (F (4, 21) = 4.46; Prob>F = 0.0091) at 5% significance level. However, only solar radiation had an individual significant effect on the yield. RH, VPD and SR had negative associations with the yield in 2Lgh with coefficients of regression of -22.95, -9.73 and -7.12, respectively. Temperature, however, had a positive relationship with yield with coefficients of regression of 37.13. The R-squared value obtained was 0.46, while the adjusted R-squared value was 0.36. The R^2 value can be said to explain 46 % of the total variability in the responses of berry yield to the 2Lgh microclimate. The regression equation is shown in Equation 2.

$$Y_{2Lgh} = 7626.3 + 37.13T - 22.95RH - 9.73VPD - 7.12SR$$

Shapiro-Wilk test was used to check the normal distribution of residuals (actual yield minus fitted yield). The probability of 86.6 % obtained for 1Lgh was greater than 5 % and this strongly suggests that the residuals were normally distributed, while the probability value obtained for 2Lgh was 5.0%. The probability value of 5% shows that the residuals for 2Lgh are barely normally distributed. The normality of the 1Lgh residuals shows that the assumption that yield is affected by environmental parameters is valid and likewise model inference (confidence intervals, model predictions).

The model was further subjected to heteroskedasticity (hettest), serial correlation and Breusch-Godfrey LM tests with the following corresponding result obtained 59.2, 74.9 and 71.6 % for 1Lgh, and 90.6, 86.10 and 84.20 % for 2Lgh. These values are all greater than a 5 % probability value which makes the models desirable for yield prediction.

Conclusion: This study investigated two single-layered and double-layered gothic greenhouses. From the comparison of the yield, microclimate parameters and yield prediction equation, it can be concluded that there was no significant difference between temperature, SR and yield, but there was a significant difference between RH and VPD. Also established was that the yield prediction equation for 1Lgh had the highest coefficient of determination. This study, therefore, has succeeded in bridging the knowledge gap by addressing the relationship that exists between greenhouse covering configuration, crop yield and greenhouse microclimate.

Conflicts of Interest: There is no conflict of interest regarding the publication of this research.

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