Rocznik Ochrona Środowiska
Volume 25 Year 2023 ISSN 2720-7501 pp. 105-115
https://doi.org/10.54740/ros.2023.011 open access
Received: April 2023 Accepted: May 2023 Published: Junly 2023

Determination of the Vertical Distribution Pattern of Indoor Climate Parameters in the Greenhouse Heated in the Winter Period

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Abstract: Ensuring the homogeneity of the indoor climate throughout the greenhouse is very important for uniform plant cultivation. In the study carried out to determine the indoor climate distribution in the heated greenhouse in the terrestrial climate, indoor temperature, relative humidity, dew point and vapour pressure deficit values were measured from 8 different measurement points. The distribution pattern of the measurement points was made horizontally and vertically at 2, 4 and 6 meters. Sensor placements are grouped vertically at 2 meters (G_1: S_1, S_2 S_3), at 4 meters (G_2: S_4, S_5, S_6) and at 6 meters (G_3: S_7, S_8). Measurements taken during the day are divided into three parts. The climatic changes in the greenhouse were monitored as daily (00:00-23:30), daytime (08:30-17:30) and night (18:00-08:00) hours. According to the results obtained from the research, it was determined that the indoor climate parameters in the greenhouse change during the average daily, daytime and night hours at different times of the day and at different locations. According to this, it has been determined that it is important for better regulation of the greenhouse climate by monitoring the changes in the plant level as it rises from the greenhouse floor to the ridge with multiple sensors instead of a single sensor.

Keywords: greenhouse, environmental control, heterogeneous environment, microclimate gradients

1. Introduction

Controlling environmental conditions in agricultural production has a direct effect on productivity. For this reason, environmentally controlled agricultural production techniques have been developing increasingly in recent years. In environmentally controlled plant production systems, natural environmental factors are tried to be changed in all aspects in line with the optimum biological demands of the plants. The most common and effective application of environmentally controlled production in plant production is carried out in greenhouses (Bayrotun et al. 2017). Despite the high yield phenomenon, the quality of greenhouse products has been the subject of significant debates in recent years. One of the main factors causing quality problems is greenhouse climatic conditions. Low temperature and high humidity, on the one hand, create physical, chemical and aromatic quality deficiencies. On the other hand, it necessitates the use of intensive agricultural pesticides. To solve the problem of low temperature and high humidity in greenhouses and to obtain high quality and high efficiency, greenhouses should be heated if the daily average temperature falls below 12°C (von Zabeltitz 2011). High humidity in unheated greenhouses causes diseases and reduces plant transpiration, thus negatively affecting plant growth (Baytorun et al. 1995, von Zabeltitz 2011). In general, points of high temperature (> 30°C) measured at the top of the greenhouse and low temperature (< 18°C) associated with high relative humidity from the middle to the bottom of the greenhouse can stress the plant. It is associated with a wide variety of plant diseases that cause damage to photosynthesis and reduced fruit quality (Hazra et al. 2007). Although suitable temperature and relative humidity values are very important for optimum plant growing conditions, the distribution of these factors throughout the greenhouse is crucial in controlling plant growth's homogeneity (Zhao et al. 2001). Therefore, it is important to determine the indoor climate distribution to improve the design of the ventilation, cooling and heating systems of greenhouses (Seo et al. 2021). However, many variables affecting greenhouse environmental conditions complicate indoor climate control and bring problems in terms of ensuring uniformity (Çaylı et al. 2016). In addition, spatial differences specific to the biological and physical aspects of the processes and systems involved make optimizing greenhouse conditions more difficult. In modern greenhouses, several measurement points are required at the plant level to create an objective and detailed view of the climate in the various regions around the greenhouses. Specific climatic gradients can cause significant differences in yield, yield, quantity and quality characteristics of plants and cause the development of various diseases (Katsoulas et al. 2017). This situation can also facilitate the formation of multiple diseases. To eliminate these temperature differences, ensure homogeneous plant growth and identify problem areas, appropriate systems are required to monitor the sensors by carefully planning and spatially correct positioning (Ferentinos et al. 2017). Recent technological developments facilitate data collection from multiple points and the analysis of these data, encouraging the development of new control strategies in greenhouses. In addition, more studies on control systems will increase greenhouse production quality and efficiency and encourage efficient use of resources (Cayli 2020). The most basic requirement for accurately monitoring environmental factors in protected crop production is the proper application and use of sensor technology. Environment variables may vary with location, orientation, size and sensor type, crop type, planting rates, season, and time. Therefore, searching for variations is a prerequisite for accurate monitoring (Ryu et al. 2014). A homogeneous greenhouse climate has economic advantages due to more homogeneous production, less disease and energy-saving possibilities. The horizontal distribution of temperature and humidity, achieved by a dense distribution of low-cost wireless sensors, helps control homogeneity by adapting the greenhouse infrastructure or selectively operating greenhouse heating and ventilation (Balendonck et al. 2010).

Greenhouses are controlled production structures that allow more products to be taken from the unit area. In addition to measuring the climate parameters in these structures with the correct methods, knowing the distribution pattern in the indoor environment during the day is very important for uniform production. Therefore, the study aimed to reveal the suitability of indoor distribution patterns in plant cultivation by measuring the temperature, relative humidity, dew point and vapour pressure deficit values during the daily, daytime and night hours in the greenhouse heated in winter.

2. Material and Method

The research was carried out in a Venlo-type glass greenhouse (8×27) m^2 in Kırşehir Ahi Evran University (39°08'02"N 34°07'08"E, 1082 m above sea level). The long axis direction of the greenhouse is North-South, the height of the gutter is 6.00 m, and the ridge height is 6.50 m. The ventilation openings are 4 windows (1×2) m^2 in the east and west directions of the roof. There is a heating system on the floor, side walls and greenhouse roof. The diameter of the heating pipes used is 51 mm. Tomatoes were grown indoors in the greenhouse. Heating was done with the automation system, which was activated automatically when the greenhouse temperature fell below 15°C. The temperature outdoors and indoors of the greenhouse, relative humidity and dew point temperature measurements were made and recorded every 30 minutes with hobo sensors between January 30 and February 06, 2022.

On-Set HOBO U12 type data loggers were used to record temperature and relative humidity values. These devices are capable of measuring temperature in the range of -20°C/70°C, with an accuracy of ±0.35°C, and proportional humidity measurement between 5% and 95% with an accuracy of 2.5%. Solar radiation measurements were made with a pyranometer connected to the sensors. The sensor measures in the measuring range of 0-1750 W/m² and has an accuracy of 5%. The front view of the location of the sensors in the greenhouse is given in Figure 1.

In the study, the distribution pattern of the measurement points was made horizontally and vertically at the 2 m, 4 m and 6 meters. Accordingly, group sensors G_1, G_2 and G_3 were placed in the greenhouse at the height of 2 meters (G_1: S_1, S_2, S_3), 4 meters (G_2: S_4, S_5, S_6) and 6 meters (G_3: S_7, S_8) from the ground.

In the study, the mean temperature, relative humidity, dew temperature and vapour pressure deficit values were determined in the greenhouse daily (00:00-23:30), daytime (08:30-17:30) and night (18:00-08:00) by taking the averages of the recorded values. The SURFER program revealed the distribution pattern in the greenhouse by using the values measured daily, daytime and night. In addition, the differences between daily, daytime and night measured values were determined with the SPSS statistical analysis program.

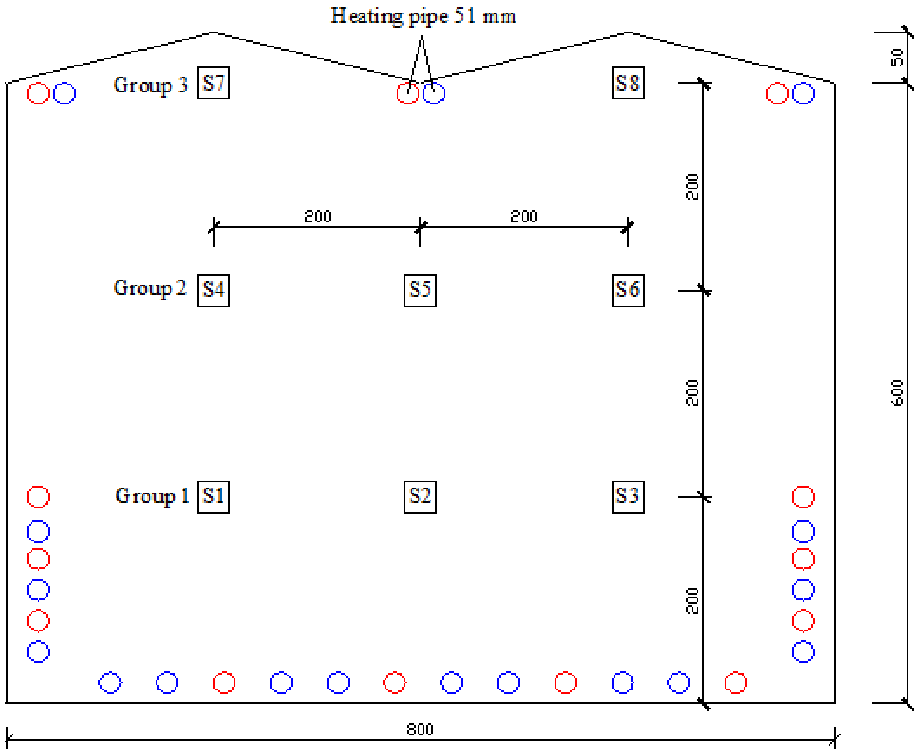

Fig. 1. Locations of sensors placed in the greenhouse

3. Result and Discussion

3.1. Temperature

The study investigated the vertical distribution of the average temperature values measured during the daily, daytime and night hours from the data loggers placed vertically in the venlo type greenhouse. The variation of the temperature values measured outdoors and indoors in the greenhouse is given in Table 1.

Table 1. Change of temperature values measured outdoors and indoors in the greenhouse

Groups	Sensors	Daily, (°C)		Daytime, (°C)		Night, (°C)	
	Outdoor/Indoor	-1.58±0.23b		1.00±0.25a		-3.31±0.31c	
G_1	1	18.48±0.26a	18.37±0.15a	23.24±0.44a	23.19±c	15.30±a	15.15±0.2a
	2	18.36±0.28a		23.47±0.48a		14.95±b	
	3	18.26±0.25a		22.85±0.44a		15.20±a	
G_2	4	18.89±0.30a	18.64±0.18a	24.27±0.54a	24.12±a	15.29±a	14.98±0.3b
	5	18.50±0.29a		23.70±0.50a		15.04±b	
	6	18.53±0.32a		24.40±0.55a		14.61±c	
G_3	7	18.16±0.30a	18.06±0.21a	23.55±0.53a	23.45±ab	14.55±c	14.45±0.3c
	8	17.96±0.30a		23.35±0.53a		14.35±d	
Mean values		18.39±0.10b		23.60±0.18a		14.91±0.02c	

According to the table, the minimum and maximum values of the hourly temperature values measured outdoors varied between -14.4°C and 9.0°C. Outdoor temperature and humidity values were measured as -1.6°C during the daily, 1.0°C during the daytime and -3.3°C at night. While the average temperature values measured indoors during the daily were 18.39°C, the highest difference measured between the averages of the sensors was 0.93°C. Considering the values measured during the daytime, the average temperatures are 23.60°C, while the highest difference between the averages of the sensors is 1.6°C. At night, while the average temperatures were 14.91°C, the highest difference between the averages of the sensors was measured as 0.9°C. The difference between the sensors in different locations of the greenhouse and the G_1, G_2 and G_3 sensors daily was found to be statistically insignificant ($p > 0.05$). Although the mean difference between the sensors during daytime hours was statistically insignificant ($p > 0.05$), the difference between the G_1, G_2 and

G_3 sensors was significant ($p < 0.05$). It was determined that the rising temperatures during the daytime increased at 4 m, and this difference started to decrease at 6 m in the roof area. At night, the difference between sensors at different locations and G_1, G_2 and G_3 sensors was statistically significant ($p < 0.05$). It has been determined that the temperatures at the 2 m, 4 m and 6 meters decrease from the greenhouse floor towards the roof area at night.

García-Ruiz et al. (2018) have investigated the greenhouse's horizontal and vertical temperature changes. Average values for horizontal differences were around 4°C in all seasons, while the maximum value was 8.4°C in spring. For vertical differences, it was observed that the average value was higher in autumn and winter, reaching values close to 4°C, while the average value was around 2°C in spring and summer. A similar situation exists for maximum values that are higher in autumn and spring and reach 10.6°C in winter. The researcher reported that the minimum values for the vertical dimension were lower than the horizontal one, as were the maximum air temperature differences for the mean value. Queiroz Zorzeto Cesar et al. (2021) vertical air temperature distribution maps show the key gradient differences between applications with the greenhouse completely closed (4.52°C), mechanical ventilation (3.86°C) with both exhaust fans on, and shading (4.04°C) with both exhaust fans on. In convection heat transfer, warm air rose as it was less dense than cold air but tended to accumulate under the plastic cover. However, it showed a decrease in the vertical temperature gradient associated with either one exhaust fan (0.67°C) or both exhaust fans (0.88°C) with roof vent openings.

Similarly, gradient differences in the vertical direction were determined in the study. As the researchers reported, these differences can increase or decrease according to the greenhouse's seasons and ventilation situation. In the study carried out during the winter months, the fact that natural or mechanical ventilation is limited in the indoor environment for energy conservation can make it difficult to reduce the gradient differences. For this reason, while the greenhouses are planned, it is important to choose the ventilation temperature required for the winter months according to the plant type grown, to mix the air homogeneously. Reducing gradient differences in measures such as the use of circulation fans is also important.

The graphical representation of the temperature distribution occurring during the daily, daytime and night hours is given in (Figure 2). When the temperature values are examined according to the sensors location in the greenhouse, it is seen that the temperature values increase daily with the effect of radiation. With the effect of decreasing temperatures in the external environment with the sunset, it was observed that the indoor temperature values also decreased. It is seen that the temperature values decrease from the greenhouse floor to the roof during night hours (Figure 2).

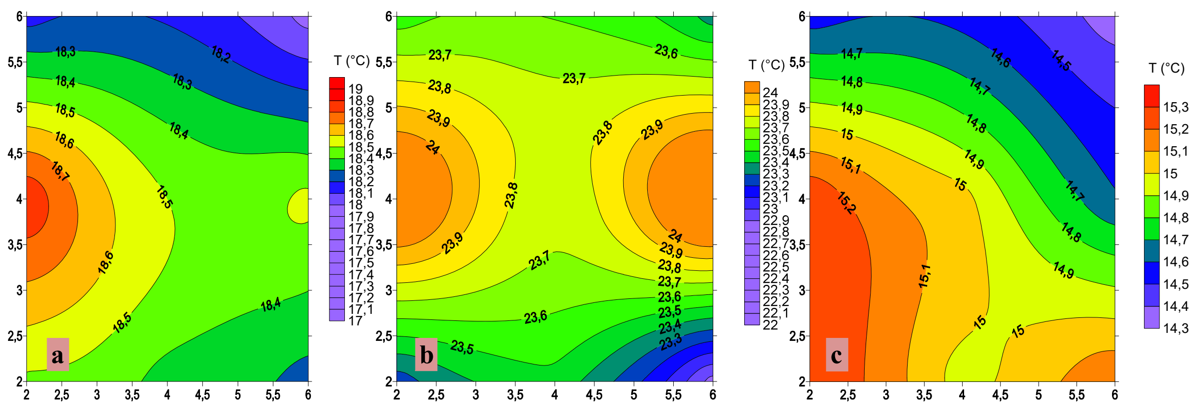

Fig. 2. The temperature distribution in the greenhouse indoor environment during the (a) daily, (b) daytime and (c) night hours

In a closed greenhouse, the rate of temperature rise is lowest at the lowest position and increases with height following the operation. When both indoor and outdoor environments were compared, an increase in indoor temperature during the day (9 and 15 hours) and a decrease in the night (3 and 21 hours) were observed. Accordingly, he reported that the greenhouse temperature and relative humidity distributions vary according to the intensity of solar radiation depending on the altitude from the ground surface and that the greatest temperature and humidity gradients occur at the peak of solar radiation at noon (Zorzeto et al. 2014). Similarly, in the study, it was observed that the highest temperature differences between the sensors during the day were observed to reach the highest value (1.6°C) during the daytime hours. García-Ruiz et al. (2018) the temperature at 1.56 m during the daytime is higher than the heights at 0.23 and 0.93 m, but the highest at 0.23 m at night and the lowest at 1.56 m. The thermal gradient is reversed because the ground acts as a thermal accumulator and transfers heat to the environment at night. According to the figure, it was determined that the air rising with the radiation effect in the greenhouse during daily and daytime hours reached the highest values at 4 m, and the temperature decreased in the roof area. At night, it was determined that the temperatures at the greenhouse floor increased due to the heat stored by the ground, and these temperatures decreased at 4 m and 6 m. Jerszurki et al. (2021) significant vertical gradients affect plant physiology, and closing curtains in winter cultivation in semi-arid/arid climates can increase fruit yield and quality. In the study, using heat curtains is very important to keep the rising temperatures in the indoor environment at the plant level on these days when the outdoor air temperatures are negative.

Greenhouse plants are mostly warm season plants that have adapted to optimum air temperatures between 17-27°C and have lower and upper limit temperatures of 10-35°C (Kittas et al. 2005). When all sensor values are considered, it has been determined that the indoor temperatures in the greenhouse where tomatoes are grown exceed the set temperature values of 15°C daily and during the daytime with the effect of the sun. It has been determined that indoor temperature values of these hours are suitable for plant cultivation. At night, it was determined that the temperature values took different values in different locations and fell below the set values. The daily variation between daytime and nighttime mean temperatures is necessary for proper physiological function. These thermal differences are between 5 and 7°C (Nisen et al. 1988). Yang (2016) stated that DIFs are an important environmental factor affecting crop growth in his study investigating the difference (DIF) between 5 different (-12, -6, 0, 6 and 12°C) day and night temperatures for tomato plants. The study's results reported that positive DIFs have a more positive effect on the plant than negative DIFs, and 6°C DIF is best for greenhouse tomato growth. The study determined that the temperature difference between day and night was 8.7°C on average. For this reason, night temperatures become important, especially for heating in the area where the research is carried out.

According to the maps and statistics, it is seen that the temperature values change depending on the outdoor environment during the daily, during the daytime and at night. Narasimhan et al. (2007) stated that the location of greenhouse sensors may reflect different values at different points of the indoor microclimate over time. Sang-yeon Lee et al. (2019) although temperature sensors are typically installed in the centre of a greenhouse for environmental control, environmental data measured at the centre of a greenhouse may not always accurately represent the entire greenhouse environment. Therefore, instead of simply placing the sensor in the centre of the greenhouse, it is necessary to select suitable sensor locations according to the greenhouse design and control strategies. Also, when the sensors are installed in various locations, it is essential to evaluate the sensor locations quantitatively. For this reason, measuring indoor temperature values using hourly climate values instead of daily averages gives more positive results. In addition, instead of a single sensor, it is very important for uniform plant cultivation to determine the distribution pattern by placing sensors at different locations in the greenhouse.

3.2. Relative humidity

The variation of the relative humidity values measured according to different sensor locations outdoors and indoors in the greenhouse is given in Table 2.

Table 2. Variation of relative humidity values measured outdoors and indoors in the greenhouse

Groups	Sensors	Daily, (%)		Daytime, (%)		Night, (%)	
	Outdoor	79.01±0.55b		72.73±0.99c		83.20±0.49a	
G_1	1	35.42±0.44ab	32.78±0.25b	31.64±0.66a	28.62±0.39b	37.95±0.54b	35.56±0.28b
	2	33.27±0.39cd		28.85±0.61bc		36.21±0.42c	
	3	29.65±0.41f		25.37±0.65d		32.51±0.45d	
G_2	4	34.65±0.46b	35.14±0.26a	30.13±0.72ab	30.41±0.40a	37.67±0.53ab	38.29±0.30a
	5	34.41±0.39bc		30.10±0.65ab		37.29±0.42ab	
	6	36.34±0.50a		30.98±0.74a		39.92±0.57a	
G_3	7	30.95±0.44e	31.95±0.32c	25.65±0.71d	26.65±0.50c	34.49±0.45d	35.49±0.32b
	8	32.95±0.44d		27.65±0.71c		36.49±0.45c	
Mean values		33.45±0.16b		28.80±0.25c		36.57±0.18a	

According to the table, the relative humidity values measured outdoors varied between 47% and 94%, with minimum and maximum values. The relative humidity values of the outdoor environment were measured as 79.01% daily, 72.73% during the daytime and 83.20% at night. However, it was determined that the relative humidity values in the heated greenhouse were low regarding plant cultivation. The relative humidity values measured in the greenhouse these days varied between 10.8% and 64.4%. Considering the relative humidity values according to its location in the greenhouse, the relative humidity values measured indoors daily were 33.45% on average, while the average highest difference measured between the averages of the sensors was 6.69%. Considering the values measured during the daytime, the average relative humidity was 28.80%. In comparison, the average highest difference measured between the averages of the sensors was 6.27%. In comparison, the average relative humidity at night was 36.57%, and the average highest difference measured between the averages of the sensors was 7.41%. As Table 2 shows, it was determined that the difference between the sensors in the indoor environment of the greenhouse was statistically significant ($p > 0.05$). It was determined that the mean difference between G_1, G_2 and G_3 sensors daily, daytime and night was significant ($p > 0.05$).

The graphical representation of the relative humidity distribution occurring during the daily, daytime and night hours is given in Figure 3. According to the figure, the relative humidity values in the 2 m are lower than in the 4 m. When the 6 m of the greenhouse is reached, it has been determined that the condensation that occurs on the greenhouse's roof reduces the relative humidity values in the roof area.

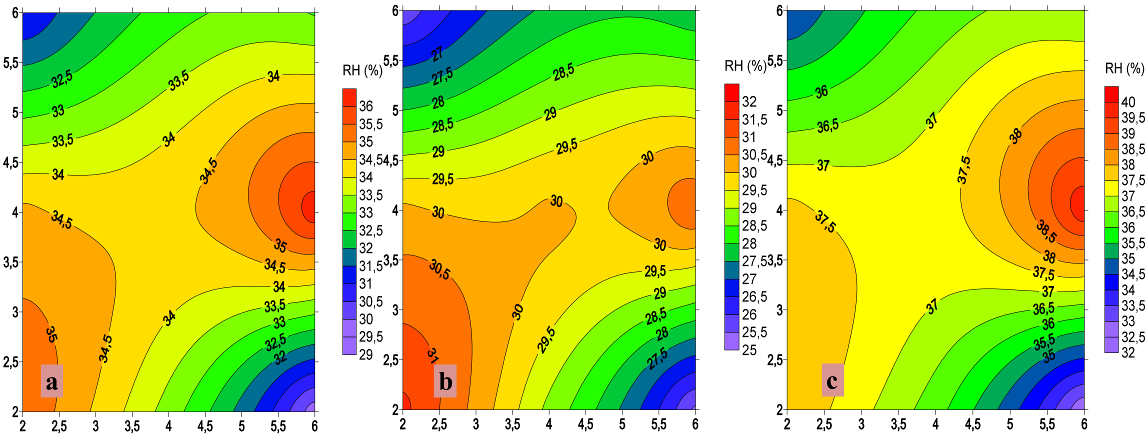

Fig. 3. Relative humidity distribution in the indoor environment of the greenhouse during (a) daily, (b) daytime and (c) night hours

As can be seen from the figure, relative humidity gradients occur at different points in the greenhouse indoor environment due to different temperature values, irrigation, plant respiration rates and plant density that occur in different greenhouse locations depending on the heating. It was determined that relative humidity values were higher during these hours due to the falling indoor temperatures at night (Figure 3). Queiroz Zorzeto Cesar et al. (2021) Opening the roof vent reduced vertical temperature and relative humidity gradients and was beneficial to achieve adequate horizontal homogeneity if the roof vents were associated with mechanical ventilation. Nowadays, indoor ventilation is very important in reducing natural and horizontal climate gradients.

In greenhouses where heat curtains are not used since the surface temperature of the cover reaches the dew point temperature due to the outdoor temperature, the humidity in the greenhouse decreases due to the condensation of the moisture in the greenhouse on the cover surface (von Zabeltitz 2011, Baytorun 2016). The decrease in relative humidity in the greenhouse with the decreasing temperature in the roof area during night hours can be explained by the decrease in the relative humidity values of the condensation occurring in the roof area. The relative humidity in the greenhouse changes depending on the leaf area index of the plant produced in the greenhouse and the external climatic conditions. When the leaf area index value of the plant produced in the greenhouse is large, the water vapour gets to the environment by transpiration increases, which causes an increase in the humidity in the greenhouse (Baytorun et al. 2019). Zhao et al. (2001), gradients of mature (2.7 m) and young plants (0.15 m) were determined using roof and roof and side wall vents. Accordingly, in mature plants, temperature and humidity were important before opening the ventilation windows and remained so after the windows were opened (roof only or both roof and side windows). Smaller slopes were observed only in the roof ventilation compared to the ventilation from the roof and side openings. The gradients in young, small plants were much smaller than in mature plants and can be assumed to be negligible for both ventilation modes. It is recommended that the optimal relative humidity range be between 50-70% during all growth stages of tomato. Studies also show that Tomato pollination increases significantly when the relative humidity is around 60%. It is recommended that the optimal relative humidity range be between 50-70% during all growth stages of tomato. Relative humidity of around 60% increases tomato pollination significantly (Harel et al. 2014). It should be underlined that plants exposed to higher temperatures need higher humidity (Kittas et al. 2005). With a single or few temperature and humidity sensors, ΔT and ΔRH values cannot be obtained accurately enough because natural variations in greenhouses are high. For certain periods in the greenhouses studied, the climate distribution within the greenhouse can be accurately predicted using at least nine sensors per hectare (33×33 m^2) (Balendonck et al. 2010). In the study, the relative humidity values measured in the greenhouse varied between 10.8-64.4%. These values were determined to be low in terms of plant breeding. In addition, the relative humidity gradients that the plants will form in the indoor environment due to different respiration rates at different growth stages will be different, as determined in the studies. For this reason, it is necessary for uniform cultivation to monitor all developmental periods of plants with sensors at different locations.

3.3. Dew point temperature

In unheated greenhouses, dew is an important problem as it causes the rapid development of fungal diseases. The study investigated the vertical distribution of the dew point temperature values measured during the daily, daytime and night hours from the data loggers placed vertically in the venlo type greenhouse. The variation of the dew point temperature values measured outdoors and indoors in the greenhouse according to different sensor locations is given in Table 3.

In unheated greenhouses, dew is an important problem as it causes the rapid development of fungal and fungal diseases. In the research, the dew point temperatures of the air in the current conditions were determined by using the temperature and relative humidity values measured indoors in the greenhouse. The study investigated the vertical distribution of the dew point temperature values measured during the daily, daytime and night hours from the data loggers placed vertically in the venlo type greenhouse. The variation of the dew point temperature values measured outdoors and indoors in the greenhouse according to different sensor locations is given in Table 3.

Table 3. Change of dew point temperature values measured outdoors and indoors in the greenhouse

Groups	Sensors	Daily, (°C)		Daytime, (°C)		Night, (°C)	
	Outdoor	-2.14±0.21b		-1.20±0.23a		-2.76±0.30b	
G_1	1	2.43±0.21ab	1.19±0.11b	4.93±0.33a	3.26±0.18b	0.76±0.20a	-0.20±0.12b
	2	1.42±0.18c		3.70±0.27b		-0.12±0.18b	
	3	-0.28±0.18e		1.13±0.27d		-1.2±0.22c	
G_2	4	2.33±0.20ab	2.33±0.11a	4.87±0.32a	4.90±0.18a	0.65±0.20a	0.62±0.11a
	5	2.02±0.18b		4.49±0.27ab		0.37±0.18ab	
	6	2.65±0.20a		5.34±0.32a		0.84±0.20a	
G_3	7	0.12±0.18de	0.24±0.13c	1.71±0.26d	2.12±0.19c	-0.93±0.21c	-1.00±0.16c
	8	0.36±0.20d		2.52±0.28c		-1.08±0.23c	
Mean values		1.38±0.07b		3.59±0.11a		-0.09±0.07c	

According to the table, the minimum and maximum values of the dew point temperature measured outdoors varied between -14.2°C and 2.5°C. Outdoor dew point temperature values were measured as -2.14°C daily, -1.20°C during the daytime and -2.76°C at night. These days, the dew point temperature values measured in the greenhouse varied between -9.4 and 21.5°C. Considering the dew point temperature values according to its locations in the greenhouse, the average dew point temperature values measured indoors during the daily were 1.38°C, while the average highest difference measured between the averages of the sensors was 2.93°C. Considering the values measured during the daytime, the average dew point temperature is 3.59°C, while the average highest difference measured between the averages of the sensors is 4.21°C. Atnight, the average dew point temperature was -0.09°C, while the average highest difference measured between the averages of the sensors was 1.92°C. In Table 3, it was determined that the difference between the sensors at different locations in the greenhouse indoor environment was statistically significant ($p > 0.05$). It was also determined that the mean difference between the sensor groups (G_1, G_2 and G_3) was significant ($p > 0.05$).

The graphical representation of the dew point temperature distribution occurring during the daily, daytime and night hours is given in Figure 4. It was determined that the dew point temperatures changed at different locations in the greenhouse according to the shape.

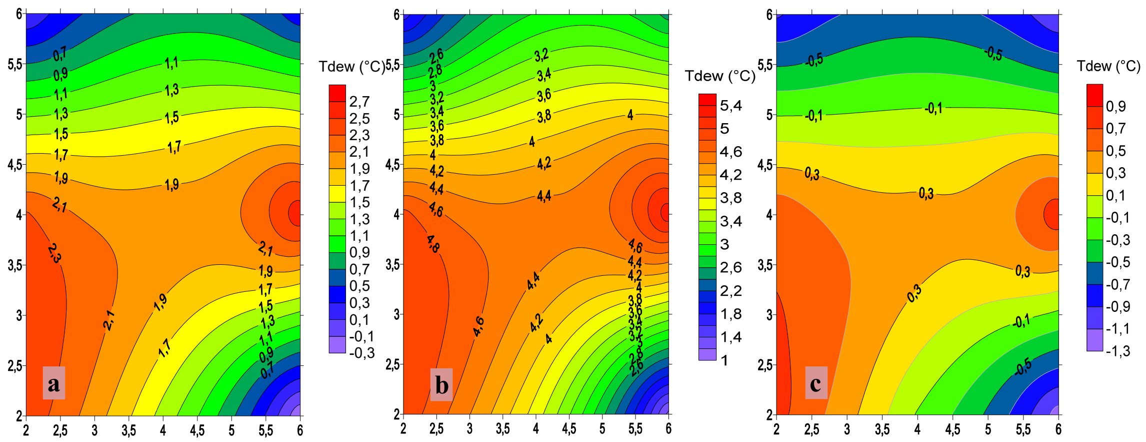

Fig. 4. Distribution of dew point temperature in greenhouse indoor environment during (a) daily, (b) daytime and (c) night hours

Fig. 4 shows that the dew temperatures are higher in this region due to the rising air temperatures at 4 m. In addition, due to the heating pipes on the side walls of the greenhouse, attention should be paid to the condensation that will occur on the surface due to the increased indoor and outdoor temperature differences in this region. In addition, the condensation occurring in the roof area at night is more important than the condensation on the side wall surfaces. Because the condensation formed here has a higher potential to fall on the plant surfaces. (Jarvis et al. 1989, Jerszurki et al. 2021) stated that the greater the nighttime humidity and the day-night temperature change, the more dew accumulates on the leaf surface. Therefore, our study is to show similarity with the findings. For this reason, it is necessary to pay attention to the condensation that occurs at night and early in the morning. In particular, dew temperatures in different greenhouse locations should be measured from different points, not with a single sensor.

An important property of cover materials is related to their condensation properties. A serious problem with cover materials is droplet condensation on the inner surface of the materials. Several undesirable effects can occur from these water droplets. These reduce solar radiation transmission due to the total internal reflection of incoming solar radiation. When small droplets combine with larger ones to drip onto plant surfaces, this promotes plant diseases (Geoola et al. 2004). Looking at the inner surface temperatures of the greenhouse cover, it changed between -7.40 and 14.23°C. Nowadays, condensation has occurred on the inner surface of the cover material, especially at night and early in the morning, when the inner surface temperature is below the dew point temperature. Çolak (2002) The dew problem in greenhouses usually occurs at night, and the dew temperature values at night are higher than during the day. In the middle of the block, where the plant density is high, the average nighttime dew temperature rises to 13.8°C. Considering that the average nighttime temperatures in these regions drop to 12.0°C, dew problems have been experienced in the greenhouse. Heating is required to prevent this. In addition, it has been reported that if the heating system is placed close to the soil surface, it will be easier to heat the plant during the rise of the heated air. Generally, floor heating in greenhouses improves air circulation within plant canopies, helping to prevent condensation on leaf surfaces. In this way, rising hot air creates air movement around the plants, keeping the plant surfaces warm and preventing condensation. The study shows that the temperature values at the plant level in the greenhouse with side wall and bottom heating are higher than the dew point temperatures, and condensation will not occur. Jerszurki et al. (2021) when the leaf temperature drops below the dew point temperature in the greenhouse at night, dew forms on the leaf surface, increasing the risk of plant diseases. As the researchers stated, it is necessary to observe the internal temperature values so that the leaf temperatures do not fall below the dew point during low temperatures in the greenhouse. This is important in terms of preventing condensation on the plant surface. Measurement points are required at different points to determine the regions where low temperature values occur in different locations of the greenhouse during the temperatures rising from the floor to the roof in the greenhouse. Measurements made with a single sensor in the middle of the greenhouse will not give reliable information about the dew temperatures in the areas close to the side walls of the greenhouse and in the roof area. It is necessary to pay attention to the high indoor and outdoor temperature differences in the heated greenhouses during winter. Greenhouse natural or mechanical ventilation systems should be activated according to the measured values, which will keep energy losses in the indoor environment as low as possible.

3.4. Vapour pressure deficit

In the study, the variation of the vapour pressure deficit values measured according to different sensor positions outdoors and indoors in the greenhouse is given in Table 4.

Table 4. Variation of vapour pressure deficit values measured outdoors and indoors in the greenhouse

Groups	Sensors	Daily, (kPa)		Daytime, (kPa)		Night, (kPa)	
	Outdoor	0.03±0.12b		0.10±0.14a		-0.02±0.05c	
G_1	1	1.49±0.04a	1.55±0.02a	2.10±0.07a	2.21±0.04b	1.08±0.01b	1.10±0.00a
	2	1.56±0.04a		2.26±0.08a		1.08±0.01b	
	3	1.59±0.04a		2.26±0.08a		1.15±0.01a	
G_2	4	1.60±0.05a	1.57±0.03a	2.38±0.10a	2.35±0.05ab	1.08±0.01b	1.05±0.01b
	5	1.55±0.04a		2.27±0.09a		1.07±0.01bc	
	6	1.55±0.05a		2.39±0.10a		1.00±0.01d	
G_3	7	1.61±0.05a	1.59±0.03a	2.42±0.10a	2.38±0.07a	1.07±0.01bc	1.06±0.01b
	8	1.57±0.05a		2.34±0.10a		1.05±0.01c	
Mean values		1.57±0.95b		2.30±1.14a		1.07±0.14c	

According to the table, the minimum and maximum values of the vapour pressure deficit values measured outdoors varied between -0.09 kPa and 0.51 kPa. Outdoor vapour pressure deficit values were measured as 0.03 kPa daily, 0.10 kPa during the daytime and -0.02 kPa at night. Vapour pressure deficit values measured indoors in the greenhouse these days have varied between 0.4 kPa and 5.8 kPa. When we look at the vapour pressure deficit values according to their location in the greenhouse, the vapour pressure deficit values measured indoors during the day were 1.57 kPa on average, while the average highest difference measured between the averages of the sensors was 0.12 kPa. Considering the values measured during the daytime, the average vapour pressure deficit is 2.30 kPa, while the average highest difference measured between the averages of the sensors is 0.32 kPa. At night, the average vapour pressure deficit was 1.07 kPa, while the average highest difference measured between the averages of the sensors was 0.15 kPa. In Table 4, it was determined that the difference between the sensors in the indoor environment of the greenhouse was statistically significant ($p > 0.05$). The mean difference between the daily G_1, G_2 and G_3 sensors was insignificant ($p < 0.05$). However, it was determined that the differences in daytime and nighttime hours were significant ($p > 0.05$).

The graphical representation of the distribution of the vapour pressure deficit occurring during the daily, daytime and night hours is given in Figure 5. According to the figure, daily and daytime vapour pressure values increased with the effect of radiation. However, it was determined that VPD values decreased during night hours.

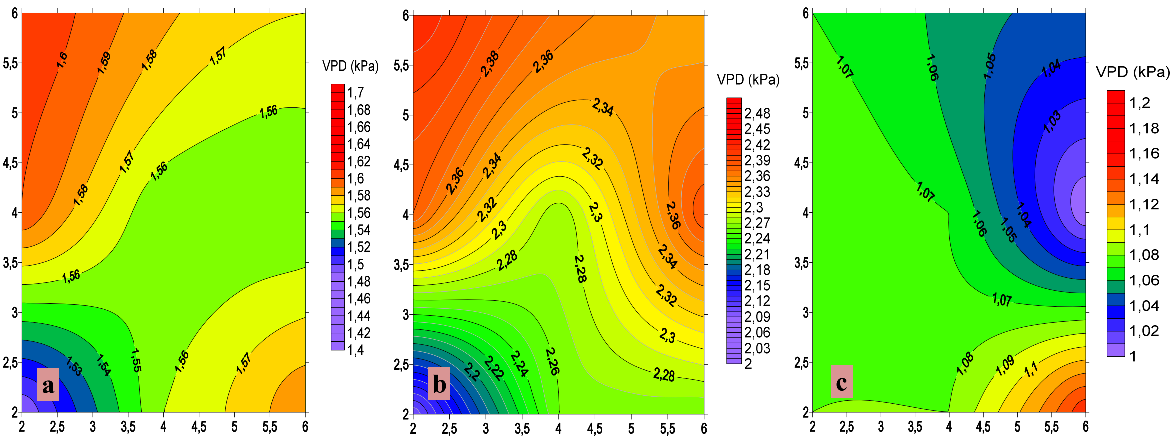

Fig. 5. Distribution of the vapour pressure deficit in the indoor greenhouse environment during the (a) daily, (b) daytime and (b) night hours

Considering the figure, increasing temperature and low relative humidity values with the effect of radiation, especially during daylight hours, caused an increase in VPD. Humidifying the indoor environment of the greenhouse with a high-pressure fogging system during the daytime is important in reducing the stress that will occur on the plant during these hours. Jerszurki et al. (2021) reported that air circulation helps to provide suitable conditions for cultivation by regulating plant temperature. Since the internal temperature values are between the temperatures required for optimum plant cultivation at these hours, it is important to ventilate the greenhouse with natural ventilation to reduce the VPD in the indoor environment. Looking at the researchers' studies on VPD, Grange & Hand (1987) stated that humidity ratios between 1.0 kPa and 1.2 kPa vapour pressure deficit have little effect on the physiology and growth of horticultural crops. Also, have been reported that low humidity levels will cause plant water stress and reduce growth, while higher levels may promote disease and cause growth and development disorders. In tomato production in greenhouses, VPD should be 0.8-0.9 kPa. This is equivalent to 70% relative humidity in conditions where the temperature is 24°C (Goldammer 2019). Barker (1990) reports that VPD values between 0.5 and 0.8 kPa are optimal for most greenhouse crops and will prevent yield reduction from fruit shrinkage and fungal diseases. Iraqi et al. (1995) suggested VPDs of 0.8 kPa as optimal during day and night hours and reported that both the photosynthesis rate and yield of tomato fruits increased when compared to 0.5 kPa VPD applications. As seen in the study, it is seen that the VPD values exceed the given limit values (0.5-1.2 kPa). The reason for this is the low relative humidity values in the indoor environment. During the daytime, indoor temperatures increase with the effect of radiation. However, ventilation in winter will cause energy loss in greenhouses. However, it was observed that the VDP values increased because the humidity in the external environment was not taken indoors with ventilation. This will adversely affect plant growth. For this reason, monitoring the temperature and relative humidity-induced VPD in the greenhouse and at the plant level is very important.

4. Conclusion

The temperature, relative humidity, dew, and vapour pressure deficit values measured daily, daytime and night in the greenhouse showed differences in different parts of the day and according to the sensor locations. Accordingly, the highest temperature gradient in the greenhouse occurred at noon. Although the temperature values measured indoors are close to the set value, depending on the outdoor temperature at night, it is necessary to pay attention to the difference between daytime and nighttime temperatures. At the same time, it is necessary to pay attention to the condensation that may occur on the cover material's surface and leaves during these hours. High temperature and low relative humidity values at noon tend to stress the plants by increasing VPD. Although the indoor environment of the greenhouse causes energy losses these days, it is important to commission ventilation systems. As can be seen, since the indoor climate of the greenhouse is not dependent on a single variable, it becomes very difficult to control the indoor climate depending on the outdoor climate, especially in winter. For a uniform climate distribution in the greenhouse, it is extremely important to measure the indoor climate parameters hourly instead of daily averages and with different sensors at different points of the greenhouse instead of a single point to make climate control more homogeneous. The control of the indoor climate (ventilation, heating, cooling) with the developing sensor technologies will help determine the measures to be taken.

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