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ANALYSIS OF CLIMATE AND VAPOR PRESSURE DEFICIT (VPD) IN A HEATED MULTI-SPAN PLASTIC GREENHOUSE

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ABSTRACT

One of the most common problems encountered in greenhouse production, i.e., high humidity, provides a favorable environment for the development of various diseases, thereby leading to significant reduction in product quality and quantity. The humidity in a greenhouse for plant growth is expressed via the vapor pressure deficit (VPD), which is an important indicator of the temperature-dependent moisture content of air. In this study, changes in the temperature-dependent relative humidity (RH) and VPD were investigated for a heated greenhouse growing different plants where is located in the Cevdetiye district of Osmaniye province in the Eastern Mediterranean Region in Turkey. For this purpose, VPD values were calculated by measuring the temperature and RH above and below the thermal screen in each compartment of the greenhouse for two months from December 2018 to January 2019, and the relationships between other climate parameters were determined using regression models. The findings revealed significant differences ($P < 0.01$) between the day and night values in all compartments. Pepper, eggplant-cucumber, and tomatoes were grown in three separate greenhouse compartments with the same structural characteristics and heating at night. The number of VPD values lower than the comfort limit was compared with the total number of measurements that were performed hourly. Values of 4.4%, 43.5%, and 36.8% (nighttime) and 3.4%, 23.6%, and 27.3% (daytime) were obtained for the greenhouses containing pepper, eggplant-cucumber, and tomatoes, respectively.

Key words: Greenhouses, Vapor pressure deficit, VPD, Greenhouse heating, Greenhouse climate

INTRODUCTION

Greenhouses are a controlled-environment agricultural structure, where high quality and high yield can be obtained in all seasons. However, for optimum efficiency, environmental conditions must be kept at an optimum level. In modern greenhouses, the aim is to provide optimum conditions with various control systems, but in most cases (especially) high humidity remains a problem. Relative humidity (RH) considers only the humidity in the air. However, compared with the RH, the temperature-dependent express moisture is a more accurate approach for plants, because the temperature-dependent moisture holding capacity of the air is variable. For this reason, the vapor pressure deficit (VPD) is an important indicator in determining the property of moisture-dependent air in the greenhouse. The VPD, which refers to the difference between the actual air pressure and the saturated air pressure, can be used to assess the disease threat, concentration potential, and irrigation needs of the greenhouse (Prenger and Ling, 2001).

Transpiration refers to the evaporation of water in plant tissues into the atmosphere. In plants, transpiration occurs through stomata. Water is absorbed with some nutrients by the roots and carried to the leaves. Evaporation occurs in the intercellular spaces within the leaf and the exchange of atmosphere and vapor is controlled by the stomatal opening. Almost all of the water absorbed by plants is lost by means of transpiration and only a small amount is used in the plant (Allen *et al.*, 1998).

While low humidity increases transpiration, high humidity prevents transpiration and reduces the water demand by the plants. Humidity in the greenhouse is affected by factors such as outdoor air humidity and water vapor, which is mostly transmitted by the plants to the greenhouse environment via transpiration.

Numerous studies have been conducted to determine the microclimate affecting pathogenic flora, and high humidity or low VPD values have been shown to cause plant diseases (Schnathorst, 1960; Grange and Hand, 1987; Hand, 1988; De Halleux and Gauthier, 1998; Talley *et al.*, 2002).

Botrytis Cinerea is one of the most common plant pathogenic fungi affecting the greenhouse plants, such as tomatoes, cucumbers, and peppers, and can lead to plant death as well as reduction in the market value of the product. For tomatoes in unheated greenhouses, this fungus infects flower fruits and leaves and can grow from leaf stem to root (Dik and Wubben, 2007).

Plant diseases can be controlled by preventing the conditions that promote disease. These conditions include moisture condensation. The growth of greenhouse pathogens on a plant requires a layer of water film. When the greenhouse air becomes saturated, condensation begins on the plant leaves and favorable conditions are provided for the occurrence of diseases. The VPD parameter can help to determine the occurrence of condensation and indicates the closeness of the greenhouse air to the saturation point (Prenger and Ling, 2001).

Very low VPD can reduce growth due to low sweating and related physiological disorders. In general, the plant leaf temperature is lower than ambient temperature (Çaylı *et al.*, 2016). Water vapor pressure above the dew point causes condensation on relatively cool plant tissue, which can lead to diseases (Körner and Challa, 2003). This condensation can also prevent pollination as pollen grains tend to remain inside or stick to the anther (Bakker, 1991). In greenhouses using microorganisms for biological control, the same environmental conditions are required for microorganisms and pathogenic organisms. Therefore, identification of a leaf surface environment supporting biological control without increasing the development of pathogenic organisms poses significant technological challenges (Jewett and Jarvis, 2001).

High VPD has a negative effect on plant growth by inducing high stomatal resistance and plant water stress (PWS). These effects are especially pronounced for tomato growth and quality characteristics (Leonardi *et al.*, 2000). VPD, which is beyond optimal for plant growth, adversely affects stoma conductivity and photosynthesis. The increase in VPD from 1.0 kPa to 1.8 kPa leads to photosynthesis depression and, in turn, major reductions in the growth of some plants (Hoffman, 1979). In addition, Shtienberg *et al.* (1998) reported that, compared with Botrytis cinerea grown from tomato stems incubated at low VPD, Botrytis cinerea progresses faster in tomato stems incubated at high VPD. Moreover, atmospheric drought or high VPD causes depression in stomatal conductivity for CO_2 diffusion (Pons and Welschen, 2003; Zhang *et al.*, 2013). Lu *et al.* (2015) reported that VPD, which increased in winter due to weather changes especially in the middle of the day, could limit plant biomass and yield. Furthermore, they reported that a significant increase in yield and biomass can be achieved with a net photosynthetic ratio by controlling VPD and, in turn, altering the leaf stomatal properties.

Monitoring of environmental conditions and control systems is an important tool for preventing losses caused by plant diseases and inappropriate environmental conditions in greenhouse management (Çaylı *et al.*, 2017; Çaylı *et al.*, 2018). Various mechanical devices and computer programs can be used to regulate the atmospheric humidity in the greenhouse. Greenhouse management is moving toward VPD-based climate control, because this approach provides direct information about the driving force of transpiration and evaporation (Zhang *et al.*, 2017).

Various methods, such as dehumidification as well as dehumidification and ventilation, can be used to adjust the water balance in the air and the greenhouse cover surfaces. In natural ventilation, humid greenhouse air is replaced with drier outdoor air by opening the ventilation windows. This method, which is common practice for reducing moisture in the greenhouse, requires no energy. For moisture condensation on a cold surface, latent heat and sensible heat collected on the surface can be returned to the greenhouse using a heat pump with the power required to operate the pump. Heat exchangers used in mechanically ventilated greenhouses provide heat exchange by mixing dry outdoor air and humid greenhouse air. Hygroscopic dehumidification, another method of adjusting the water balance in air, has been rarely investigated. The equipment required for this method is very complex and the greenhouse is unsuitable for use of the necessary chemicals. In this method, humid greenhouse air is contacted with hygroscopic material, which releases the latent heat of evaporation when water vapor is absorbed (Campen *et al.*, 2003).

Using simulations, De Halleux and Gauthier (1998) compared dehumidification through ventilation and proportional ventilation and reported that 18% more energy is used during proportional ventilation, i.e., the more efficient of the two methods. Campen *et al.* (2003) compared three different methods (condensation of moisture on a cold surface, mechanical ventilation by heat pump, and condensation of moisture on a hygroscopic material) with natural ventilation. They reported that applications with moisture condensation on the heat pump and on the surface are quite costly, and that the method of dehumidification with a hygroscopic material is advantageous because the latent heat is directly converted to sensible heat. Campen and Bot (2002) performed dehumidification using finned pipes fixed under a greenhouse gutter. In the study, water cooled under the dew point temperature was passed through pipes and 40 L h^{-1} m^{-2} condensation water was obtained during the minimum ventilation periods. Only one third of the total heat energy associated with 80% humidity conditions of greenhouse air could be transferred to greenhouse air.

Heating in greenhouses is an air conditioning measure that limits the development of disease infections (Baytorun *et al.*, 2018). In heated greenhouses, Botrytis infection is almost entirely limited to root infection (Dik and Wubben, 2007).

The effects of greenhouse air conditioning measures on plant health and growth have been extensively studied. For example, several studies investigating disease pathogen survival at different climatic levels have revealed two critical values of VPD. Studies show that VPDs of <0.43 kPa and <0.20 kPa are optimal for survival of fungal pathogens and damage induced by disease infections, respectively (Elad *et al.*, 1996). VPD levels of 0.2 kPa–1.0 kPa have little effect on the physiology and growth of horticultural plants (Grange and Hand, 1987). However, some authors have observed that low VPDs have a positive effect on dry matter accumulation and may also promote the incidence of calcium-induced physiological disorders in leaves, without symptoms of calcium deficiency in fruits (De Kreij, 1996). The effects of VPD have been studied frequently during the winter period when very high air humidity occurs frequently in the greenhouse. However, the reduction of moisture for increasing the VPD level to >0.3 kPa has been deemed unsuitable, because this increase leads to a reduction in efficiency (Holder and Cockshull, 1990).

The VPD parameter plays an important role in the evaluation of the greenhouse climate. This parameter is used especially for determining the disease and moisture-condensation risk as well as irrigation needs of a greenhouse. Although no fixed-limit VPD value exists and this parameter varies depending on the plant grown, values ranging from 0.2 kPa to 1.2 kPa are generally desired. In the greenhouse environment, the contribution of different plant species to the indoor VPD may differ. The VPD may also be affected by heat-saving applications (such as a thermal screen) as well as greenhouse heating and outdoor climatic conditions.

In this study, climatic conditions and VPD values were monitored in a heated greenhouse and temporal changes in the VPD were evaluated. Furthermore, changes in the indoor VPD values for different plant species and the applicability of the determined VPD values were examined with regards to each greenhouse compartment. Moreover, VPD regression models were developed depending on the climate parameters.

MATERIALS AND METHODS

The research was performed in a greenhouse located in Cevdetiye district of Osmaniye province in the Eastern Mediterranean Region of Turkey (37.131; 36.203, WGS84) and based on the data measured between December 1, 2018, and January 31, 2019. The research was conducted based on the data measured between December 1, 2018, and January 31, 2019. This greenhouse has a gothic roof, consisting of three compartments, is covered with polyethylene (PE) plastic, and consists of 15 spans. The first compartment consists of four spans and the other two consist of five spans. One of the spans is used for the service area.

The compartments were divided by polycarbonate (PC) material. Pepper, eggplant, and tomatoes were grown in the first compartment (C-1), second compartment (C-2), and third compartment (C-3), respectively. Natural ventilation was provided with roof ventilation in each span. Ventilation openings constituted 40% of the floor area and an insect net was used. Aluminum pipes used for heating were placed between the rows of plants. Heating is provided by a central heating system and compressed natural gas (CNG) is used as fuel. The heating was set to 15 °C and ventilation began automatically at temperatures above 20 °C, using the greenhouse automation control system.

The aluminum strip acrylic thermal screen used for energy saving has a shading rate of 55% and an energy saving rate of 58%. The thermal screen was opened at 08.00 and closed at 17.00. The technical features of the greenhouse are listed in Table 1, and a schematic as well as pictures of the greenhouse are provided in Fig. 1.

Table 1. Technical characteristics of research greenhouse.

Greenhouse features	Values
Ventilation	Roof ventilation
Roof wall cladding	0.180 mm Polythene (PE)
Side wall cladding	8 mm Polycarbonate (PC)
Number of spans in each compartment	Five (one of the spans for service use)

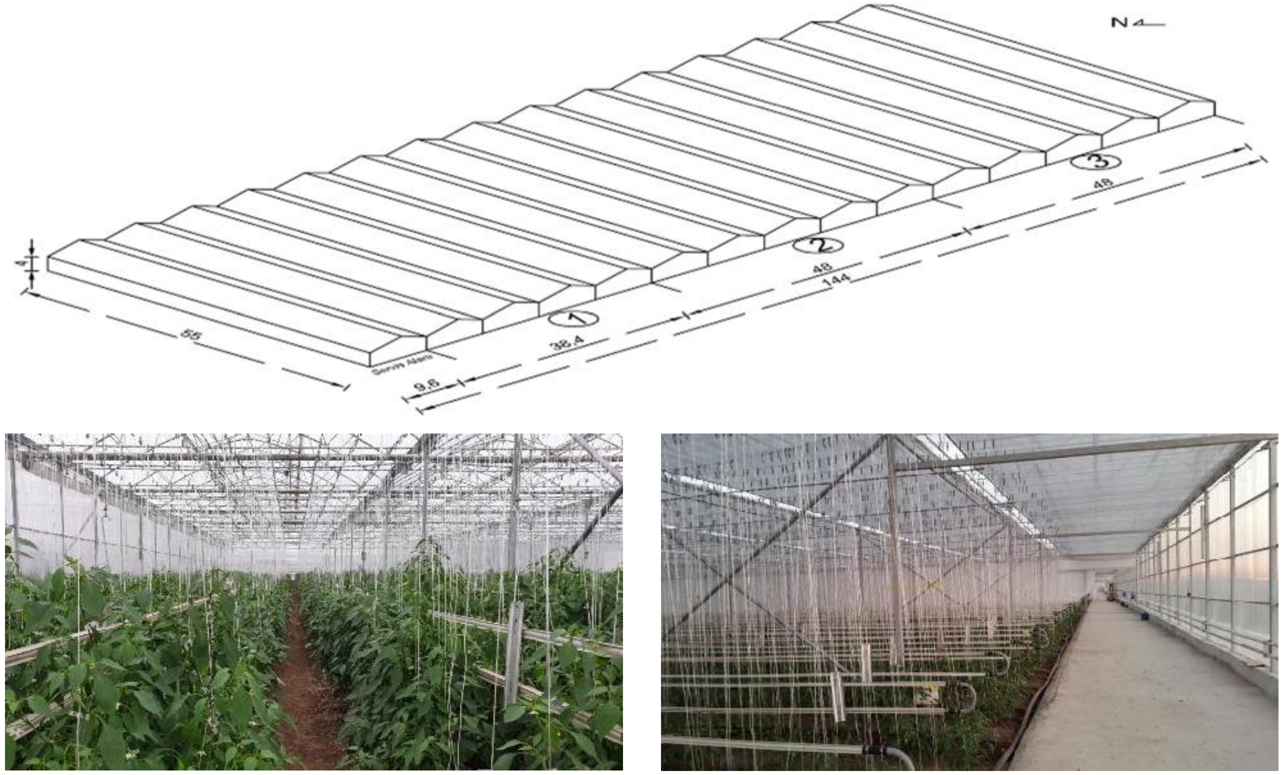

Fig. 1. Geometry and views of the greenhouse

HOBO-U12 data logger was used for temperature and RH measurements. Data loggers are capable of measuring temperature in the range (-20) - +70 °C with an accuracy of ±0.35 °C and measuring RH with an accuracy of 2.5% in the range 5 - 99%. In the greenhouse compartments, the data recorders under the thermal screen were located at a height of 1 m from the floor. Similarly, the data recorders on the thermal screen were placed at a height of 5.5 m from the floor between the thermal screen and the ridge. The temperature and RH values were recorded at 1-hour intervals. The outside temperature was recorded with the same model data logger at 2 m above the ground. Measurements in the greenhouse were performed for a total of 1488 h in two months between December 1, 2018 and January 31, 2019.

The VPD value of the air at a given temperature is equal to the difference between the saturated vapor pressure (e^o) and the current vapor pressure (e_a). This value is calculated from the following relation:

$$V \quad = e^o - \ e_a \tag{1}$$

The saturated vapor pressure, which depends on the air temperature, was calculated as follows (Allen *et al.*, 1998):

$$e^o(T) = 0.6108e \quad \left\lfloor \frac{1\ .2\ \ T}{T+2\quad .3} \right\rfloor \tag{2}$$

Where, $e^o(T)$ is the saturated vapor pressure of the air (kPa) and T is the air temperature (°C).

The dew point is the cooling temperature required for saturation of the air. Therefore, the actual vapor pressure is equal to the saturated vapor pressure at the dew point temperature and is calculated as follows (Allen *et al.*, 1998):

$$e_a(T_{d_i} \quad) = 0.6108e \quad \left\lfloor \frac{1\ .2\ \ T_{d_i}}{T_{d_i}\quad +2\quad .3} \right\rfloor \tag{3}$$

Where, $e_a(T_{d_i} \quad)$ is the vapor pressure of the air at the dew point temperature (kPa) and T_{d_i} is the dew point temperature (°C).

In this study, the data set obtained from hourly measurements, in order to investigate the relationship between indoor and outdoor temperatures and RH and VPD, was divided into two groups: night (20.00–07.00) and day (08.00–19.00) for each greenhouse compartment. For plant comfort range, we selected lower and upper VPD limits of 0.2 kPa and 1.2 kPa, respectively. VPD was calculated with temperature values based on measurements, and the VPD values remaining within the selected comfort range were then calculated proportionally. To determine the best RH–Temperature, VPD–RH, and VPD–Temperature relationships, different linear and nonlinear regression models were used to identify the model equations yielding the VPD associated with the highest R^2 values.

RESULTS AND DISCUSSION

Descriptive statistics are given in Table 2 for day and night temperature and RH values measured in three different greenhouse compartments during the research period.

Table 2. Descriptive statistics for greenhouse climate data.

Comp,	Min				Max				Mean				Std. deviation			
	Temp (°C)		RH (%)		Temp (°C)		RH (%)		Temp (°C)		RH (%)		Temp (°C)		RH (%)	
	Day	Night	Day	Night	Day	Night	Day	Night	Day	Night	Day	Night	Day	Night	Day	Night
C-1	8.6	11.4	23.4	23.4	30.7	19.4	95.3	99.5	18.13	15.4	43.4	53.5	3.6	1.4	20.2	19.1
C-2	8.6	11	23.5	59.6	28.7	18.3	99.5	99.5	16.5	14.9	75.2	86.6	2.7	1.5	20.0	10.2
C-3	8.2	11	23.7	65.9	28.3	19.4	99.5	99.5	16.7	15.2	73.1	86.2	2.8	1.5	21.2	8.8
Outside	-0.6	-2.0	23.4	27.0	21.7	17.5	99.5	99.5	12.3	8.7	53.7	68.2	3.8	3.7	22.2	21.1

As shown in the table, the minimum daytime and minimum nighttime temperatures are 8.2 °C and 11 °C, respectively. These low temperatures may have resulted from the short-term decrease in temperature during periods when the ventilation windows were open. In the greenhouse, which is heated at night, low temperatures (11 °C) may have resulted from forced ventilation due to excessive humidity. Ventilation also yielded low RH values.

The mean temperature was close to the heating set point temperature, and the mean RH in C-1 was lower than that in the other compartments. Moreover, the leaf area index (LAI) of pepper was small in this compartment and, hence, the transpiration-induced increase in moisture may be less than the increase in other compartments. Descriptive statistics for VPD calculated from the measured temperature and RH values in three different compartments of the research greenhouse are provided in Table 3.

Table 3. Descriptive statistics for VPD in all greenhouse compartments.

Case	N	VPD (kPa)				Skewness		Kurtosis	
		Min	Max	Mean	Std. Deviation	Statistic	Std. Error	Statistic	Std. Error
C-1 (Day)	806	0.07	2.51	1.0036	0.5321	0.266	0.086	-0.989	0.172
C-2 (Day)	806	0.00	2.26	0.4883	0.4516	1.31	0.086	1.013	0.172
C-3 (Day)	806	0.00	2.01	0.5539	0.4962	0.986	0.086	-0.243	0.172
C-1 (Night)	682	0.02	1.21	0.6478	0.2858	-0.149	0.094	-1.216	0.187
C-2 (Night)	682	0.00	0.58	0.2197	0.1499	0.221	0.094	-0.673	0.187
C-3 (Night)	682	0.00	0.52	0.2366	0.1389	-0.291	0.094	-1.313	0.187
Outside	806	0.00	1.90	0.6833	0.4227	0.357	0.086	-0.807	0.172

As shown in the table, the minimum VPD values of each compartment of the greenhouse were close to zero, indicating that the greenhouse air was almost completely saturated. The maximum values exceeded 2.0 kPa during the daytime and remained within the plant comfort range in the C-2 and C-3 compartments during the nighttime. Due to the low outdoor RH during daylight hours when the ventilation windows were opened, the VPD fell outside the plant comfort range. However, the average VPD values indicated that the plant comfort range is realized in all cases and in all compartments.

Evaluation of VPD in terms of plant comfort: According to previous studies, VPD values ranging from 0.2 kPa to 1.2 kPa yield the best plant growth and optimum water consumption and are unfavorable for plant diseases (Elad *et al.*, 1996). Fig. 2 shows the VPD values calculated based on measurements performed in the greenhouse compartments.

Fig. 2 shows that in the C-1 compartment, VPD occurred in the normal range for both and day and night. Oftentimes, the VPD value was lower than the comfort limits due to high RH at night. Furthermore, VPD values lower than 0.2 kPa were obtained 4.4%, 43.5%, and 36.8% (night-time) and 3.4%, 23.6%, and 27.3% (daytime) of the total time (1488 h) for C-1, C-2, and C-3, respectively. The daytime VPD values of each compartment differed significantly (P<0.01) from the corresponding nighttime values, which, in turn, differed significantly (P<0.01) from each other.

Investigation of temperature-VPD and RH-VPD relationship: In this study, temperature-VPD and RH-VPD relationships were investigated separately (day and night) for each compartment, to determine the effect of different plants on the ambient air in heated greenhouse compartments having the same structural characteristics.

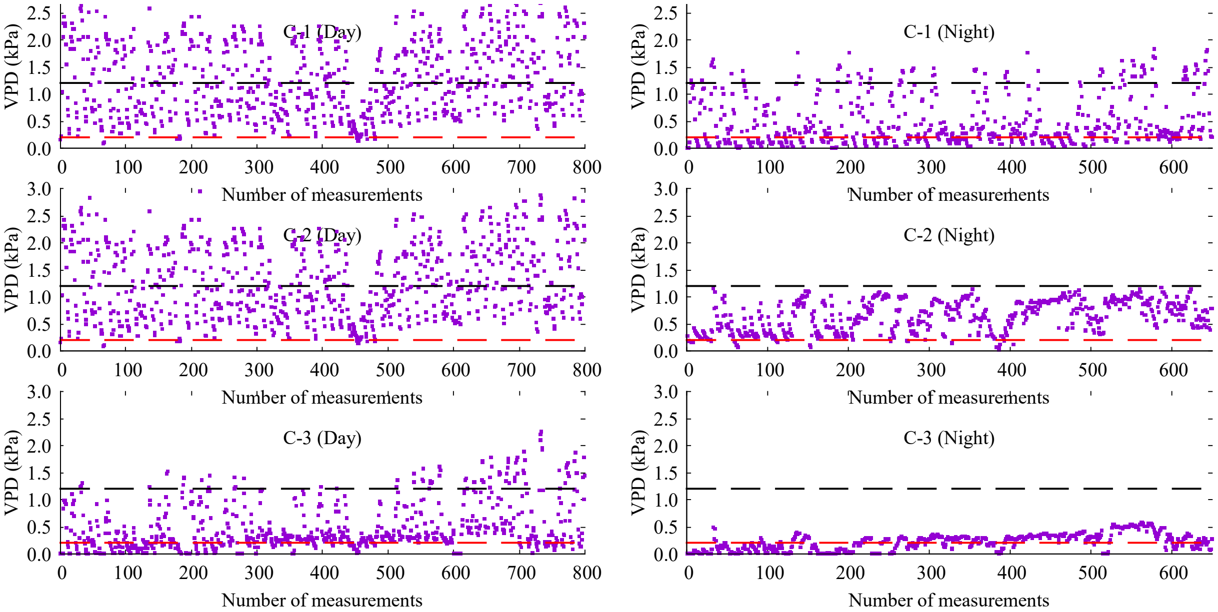

Fig. 2. VPD values in greenhouse compartments and recommended upper-lower limits

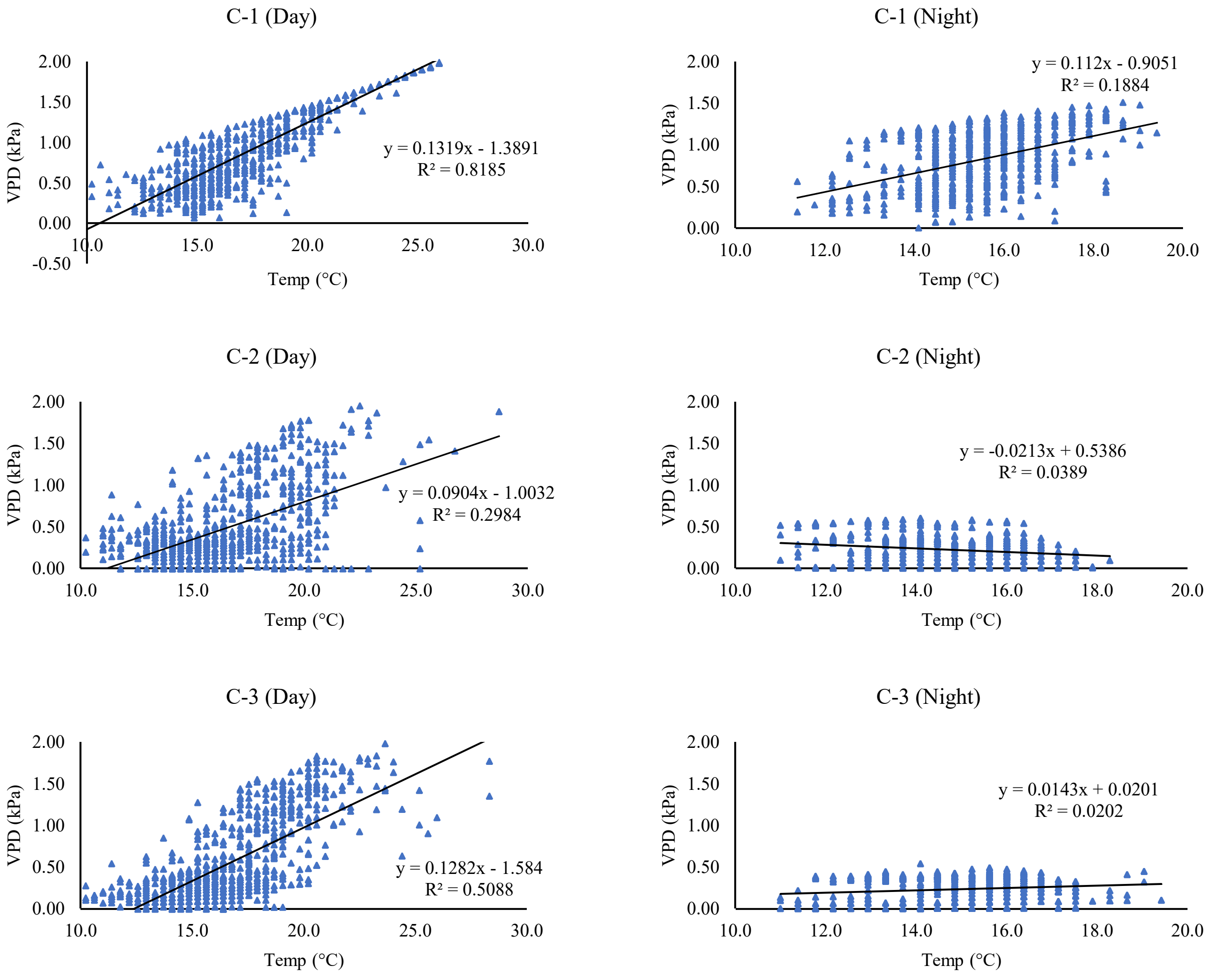

Fig. 3. VPD value as a function of temperature

A significant correlation was obtained between the VPD and the daytime temperature in each compartment. However, for the night, a strong correlation was obtained only for C-1. The nighttime temperatures and VPDs of the C-2 and C-3 compartments seemed uncorrelated, i.e., although the temperature increased, the VPD changed only slightly. Fig. 4 shows the relationships between RH and VPD.

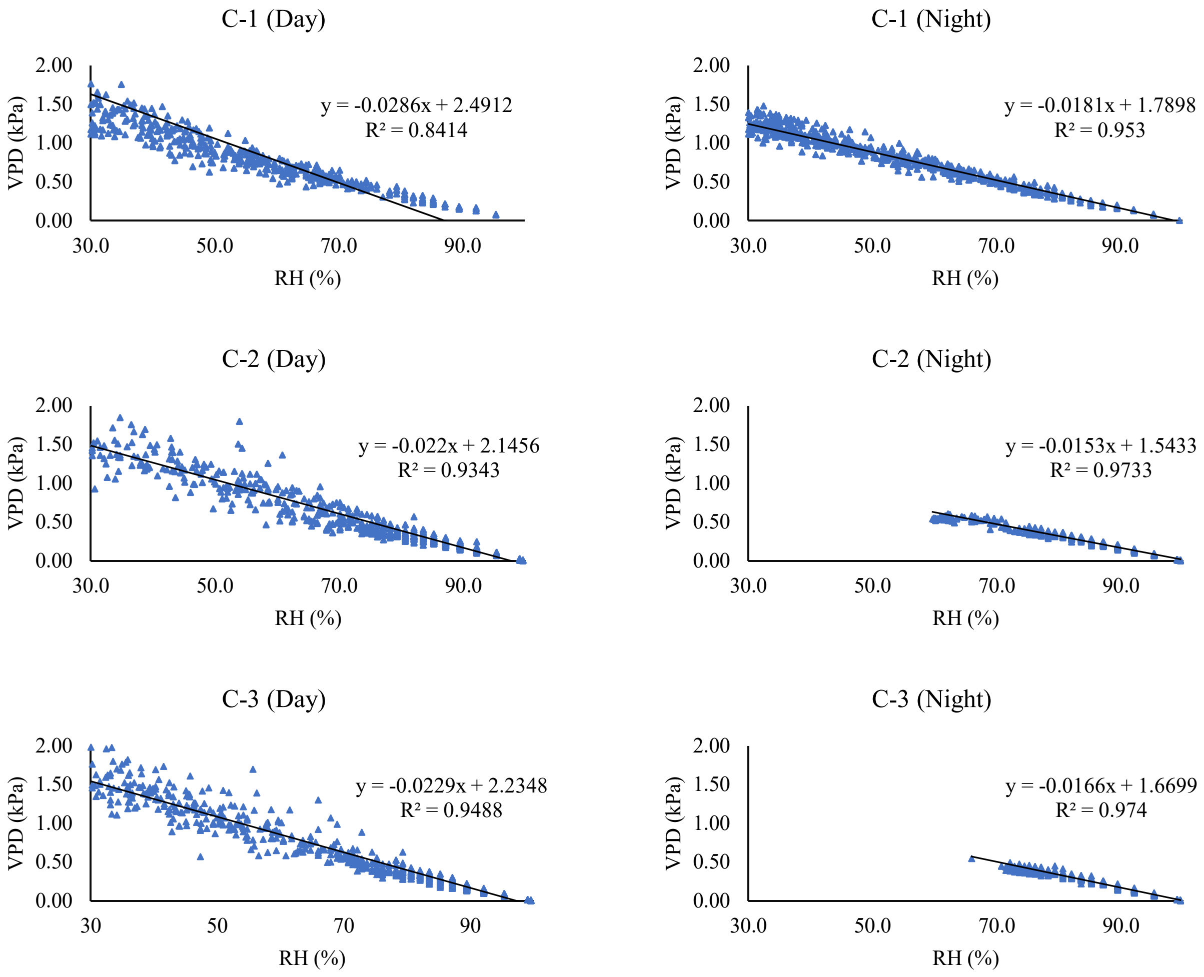

Fig. 4. VPD value as a function of RH

As shown in Fig. 4, VPD is inversely related to both day and night RH, i.e., VPD decreased with increasing RH. The best VPD-RD correlations were determined using linear and nonlinear regression models (see Table 4).

Table 4. VPD regression model equations as a function of temperature and RH.

CASE	VPD=f(x=T)	R^2	VPD=f(x=RH)	R^2
C-1 (Day)	VPD=0.1319T-1.1389	0.8185	$VPD=3.9886e^{-0.031RH}$	0.9282
C-2 (Day)	VPD=0.0904T-1.0032	0.2984	VPD=-0.0220RH+2.1456	0.9343
C-3 (Day)	VPD=0.1282T-1.5840	0.5088	VPD=-0.0229RH+2.2348	0.9488
C-1 (Night)	VPD=0.1120T-0.9051	0.1884	VPD=-0.0181RH+1.7898	0.9530
C-2 (Night)	VPD=0.0213T+0.5386	0.0389	VPD=-0.0153RH+1.5433	0.9733
C-3 (Night)	VPD=0.0143T+0.0201	0.0202	VPD=-0.0166RH+1.6699	0.9740

The ventilation in the greenhouse was operated during the day. At night, the heating system was operated and the thermal screen was closed for heat saving. Two different climatic zones occurred above and below the thermal screen in each compartment of the greenhouse. Although isolated from the plant air, the on-screen volume can affect VPD values, owing to air movement, leakage, and other factors. Similar changes in the greenhouse air properties were observed for all days and, hence, changes in the VPD values for only one day were examined (see Fig. 5).

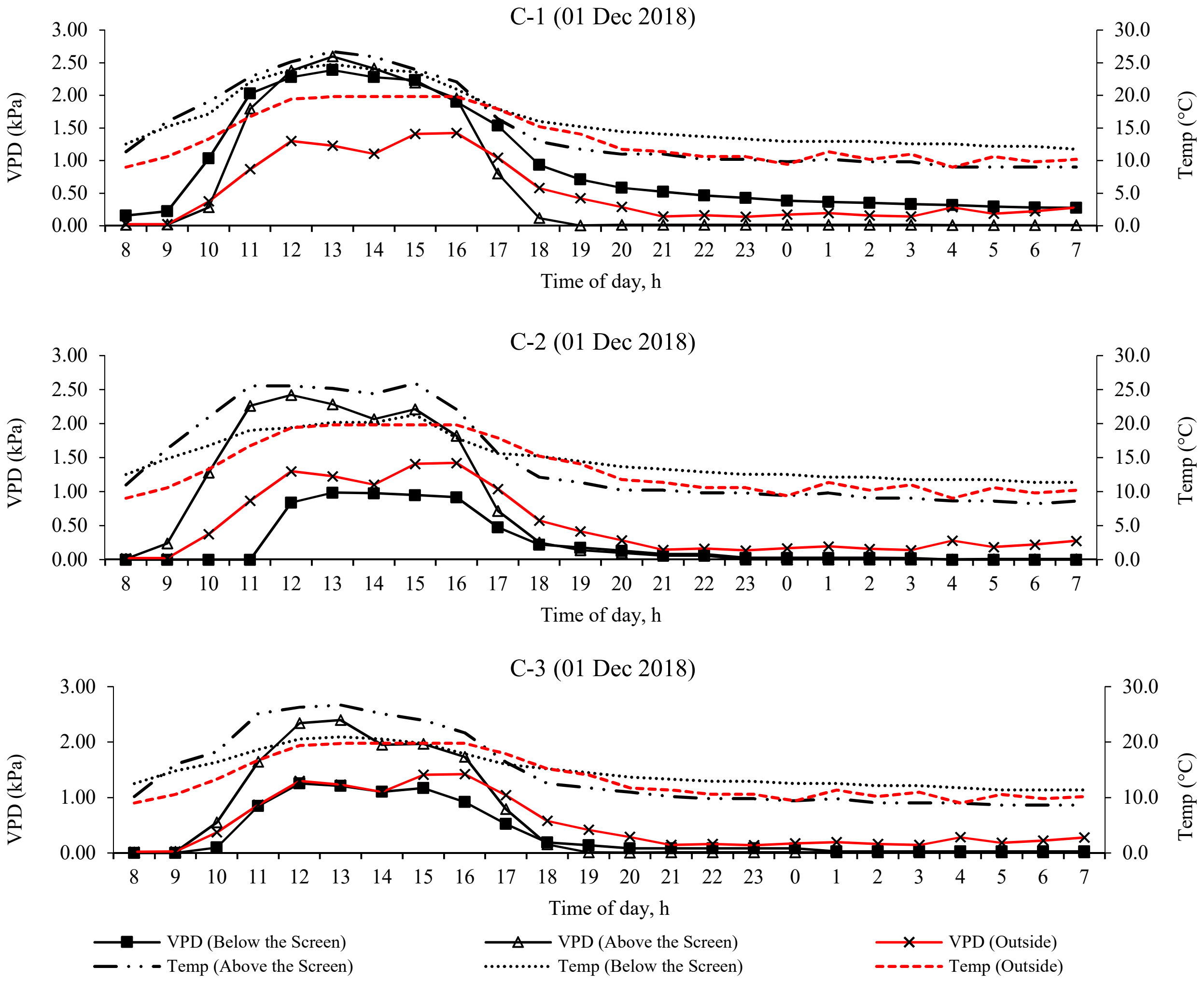

Fig. 5. Daily changes in VPD and temperatures below and above the thermal screen

When the daytime ventilation windows and the thermal screens were opened, the VPDs of C-2 and C-3 were only equalized to the outdoor value, despite the rapid rise in the VPD of C-1 (see Fig. 5). This is attributed to the different transpiration rates of different plants in each compartment. In cucumber-growing C-2 and tomato-growing C-3, the VPD value became equal to the outdoor values at 14.00 and started to decrease rapidly when the ventilation windows were closed at 17.00 during the evening hours. The VPD on the thermal screen is always higher than the values below the screen. The opposite trend occurred at night, because the night-time temperatures were lower than the daytime temperatures, thereby resulting in low VPD values. At night, the temperature below the thermal screen and the temperature above the screen ranged from 10 °C to 14 °C and 8.5 °C to 11 °C, respectively. A similar trend was observed for all compartments and the VPD values below the thermal screen differed significantly (P<0.01) from the values above the screen in all three cases.

Relationship between indoor and outdoor temperature, RH, and VPD: Plastic-based greenhouse covers are quite resistant to heat fluxes, but are quite permeable to far infrared radiation (FIR) (Von Zabeltitz, 2011). Therefore, outdoor climate conditions are an important parameter in indoor heat balance. At the same time, the plant species in the indoor environment and the metabolic activities of these species may yield different indoor-outdoor relations for a given compartment (Fig. 6).

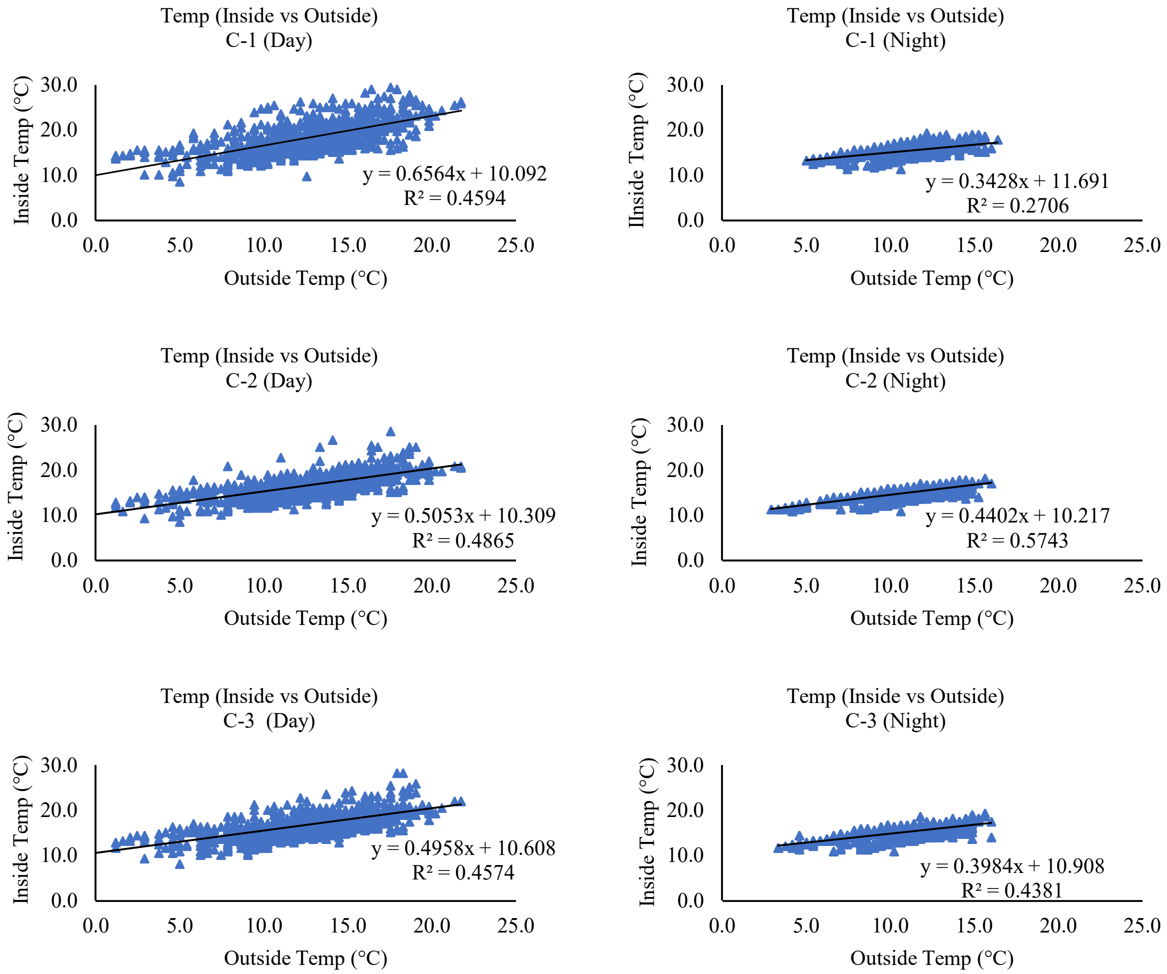

Fig. 6. Indoor-outdoor temperature relations

The typical correlations observed for the day and night indoor-outdoor measurement data are shown in Fig. 6. However, this relationship is more significant during the day (than during the night) and data is collected in a certain area at night. At the same time, the heating effect in the greenhouse is quite evident at night. Regression models of the above graphs are given in Table 5.

Plant species and metabolism are effective in transpiration. The greenhouse cover allowed heat transfer, but prevented moisture transfer. Therefore, the moisture generated by the transpiration remained in the greenhouse and could produce different results and relationships for different plant species of a given compartment, as shown in Fig. 7.

Table 5. Regression models for indoor temperatures as a function of outdoor temperature.

CASE	T_{in}=f(x=T_{out})	R²
C-1 (Day)	T_{in}=0.6564T_{out} + 10.092	0.459
C-2 (Day)	T_{in}=0.5053T_{out} + 10.309	0.487
C-3 (Day)	T_{in}=0.4958T_{out} + 10.608	0.457
C-1 (Night)	T_{in}=0.3428T_{out} + 11.691	0.271
C-2 (Night)	T_{in}=0.4402T_{out} + 10.217	0.574
C-3 (Night)	T_{in}=0.3984T_{out} + 10.908	0.438

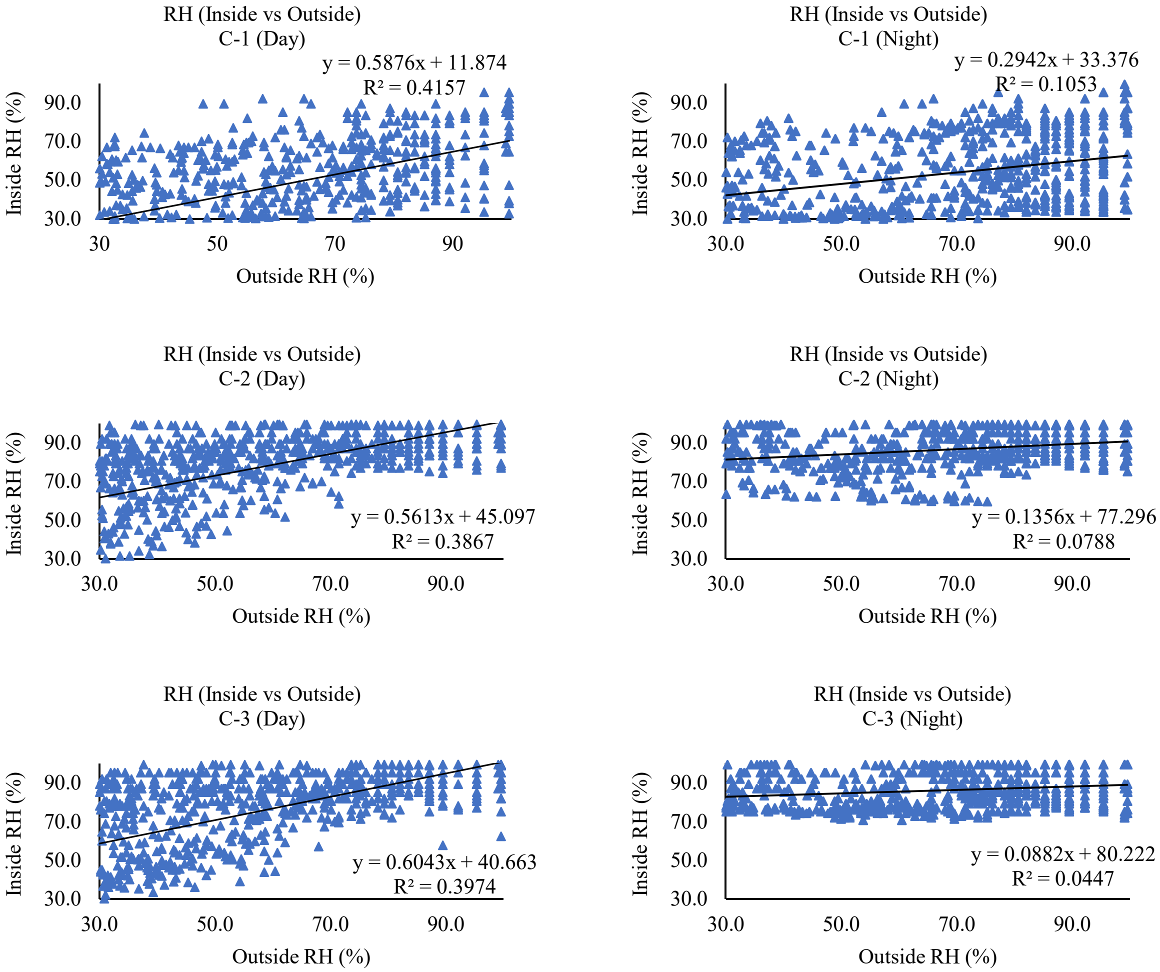

Fig. 7. Indoor-outdoor RH relationships

Although the trends differed significantly among the greenhouse compartments during the day, significant correlations (P <0.01) were obtained (see Fig. 7). However, in the greenhouses during the daytime, high RH was often observed for the C-2 and C-3 compartments. This indicated that the plants in these compartments obtain moisture mainly via transpiration and ventilation is insufficient. Similar coefficients were obtained for the day and for each correlation (*Pearson correlation: C-1=0.645, C-2=0.622, C-3=0.630*). The correlation for the nighttime hours, although significant, was lower than that obtained for the daytime hours (*P<0.01, Pearson correlation: C-1=0.347, C-2=0.290, C-3=0.223*). Regression models of the above graphs are listed in Table 6.

Temperature and RH are effective parameters for VPD, which plays an important role in defining the appropriate plant growth environment. The outdoor temperature and RH are effective parameters for the greenhouse environment and, hence, the indoor VPD may be correlated with the outdoor VPD. Therefore, the relationship between these values was investigated (see Fig. 8).

Table 6. Regression models for indoor RH as a function of outdoor RH.

CASE	$RH_{in}=f(x=RH_{out})$	R²
C-1 (Day)	$RH_{in} = 0.5876RH_{out} + 11.874$	0.416
C-2 (Day)	$RH_{in} = 0.5613RH_{out} + 45.097$	0.387
C-3 (Day)	$RH_{in} = 0.6043RH_{out} + 40.663$	0.397
C-1 (Night)	$RH_{in} = 0.2942RH_{out} + 33.376$	0.105
C-2 (Night)	$RH_{in} = 0.1356RH_{out} + 77.296$	0.079
C-3 (Night)	$RH_{in} = 0.0882RH_{out} + 80.222$	0.045

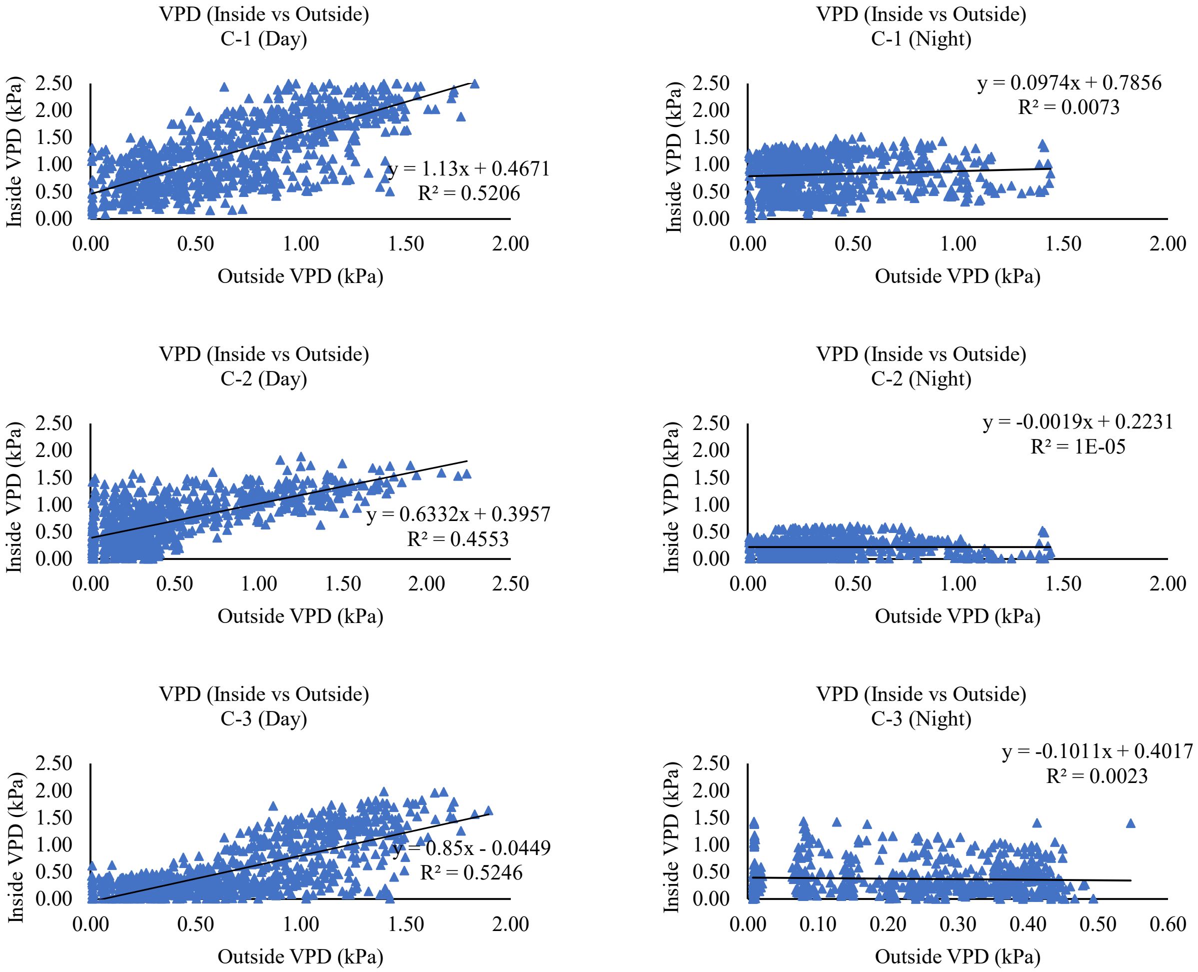

Fig. 8. Indoor-outdoor VPD relationships

The trend observed for the indoor-outdoor RH are similar to those observed for the indoor-outdoor VPD. During the day, the ventilation effect yielded a significant relationship between the indoor and outdoor environments. Correlation analysis revealed significant correlation between indoor and outdoor VPD values of each compartment during the daytime ($P<0.01$, *Pearson correlation: C-1=0.722, C-2=0.675, C-3=0.724*). At night, significant correlation was found only in C-1 ($P<0.05$). Furthermore, negligible correlation was obtained for the indoor and outdoor VPD values of the C-2 and C-3 compartments. Table 7 shows regression models considering the indoor VPD as a function of the outdoor VPD.

Table 7. Regression models for indoor VPD as a function of external VPD.

CASE	$VPD_{in}=f(x=VPD_{out})$	R²
C-1 (Day)	$VPD_{in}=1.13VPD_{out} + 0.4671$	0.5206
C-2 (Day)	$VPD_{in}=0.6332VPD_{out} + 0.3957$	0.4553
C-3 (Day)	$VPD_{in}=0.85VPD_{out}-0.0449$	0.5246
C-1 (Night)	$VPD_{in}=0.0974VPD_{out} + 0.7856$	0.0073
C-2 (Night)	$VPD_{in}=-0.0019VPD_{out} + 0.2231$	1E-05
C-3 (Night)	$VPD_{in}=-0.1011VPD_{out} + 0.4017$	0.0023

Conclusion: Greenhouse plant cultivation is a production system that requires very precise control. If the climate is properly controlled, large and high-quality yields can be obtained. Acceptable limits of 70%–90% are recommended for the humidity, which is one of the most common problems in greenhouses. However, the RH, which is expressed proportionally, is temperature dependent. In addition, the amount of water vapor released by plants into the air, via transpiration, depends on the saturation of the air. The VPD, i.e., the difference between the saturated pressure of the air and the current air pressure, must lie within the ideal limits to enable plant-climate adjustments and adequate water intake.

Ventilation is impossible with heating and, hence, critical VPD levels occurred repeatedly, especially in compartments with large leaf area indices (e.g., those associated with tomato at night). Ventilation is an important climate control factor. However, ventilation and simultaneous heating at night cause energy loss. For this reason, including dehumidification systems and heat-saving measures in the design and feasibility stage of modern greenhouses would be useful.

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