

Computation of vapour pressure deficit and crop transpiration via development of a web based computer module

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ABSTRACT

The plant water or nutrient requirement under greenhouse conditions is mainly governed by crop transpiration in a linear relation to vapour pressure deficit (VPD), particularly in soilless production systems. Being a cooling process in plants, transpiration governs the plant water requirement in relation to the subjected microclimatic conditions and VPD can be used as a tool to maintain greenhouse crop transpiration to optimal range for obtaining desired crop yields. Thus, the present investigation was undertaken to study the integrated effect of temperature (T_{apc}), relative humidity (E_{apc}) and solar radiation (I_{rad}) on VPD and crop transpiration. A computer module was developed to monitor the behavior of the VPD and thereby the crop transpiration through charts under greenhouse conditions. The VPD indicated a linear increasing trend with T_{apc} ($R^2 \geq 0.84$) and decreasing trend with E_{apc} ($R^2 = 0.99$), demonstrating a strong correlation in both cases. The increasing crop transpiration with VPD, particularly under hot climatic conditions significantly increased the input water and nutrient requirements of the crop. Thus, transpiration in relation to VPD should be considered as a factor for fertigation scheduling and improving irrigation control in soilless systems. Moreover, maintaining T_{apc} , E_{apc} and VPD within range of 22-27°C, 60-80% and 0.53-1.10 kPa may help to control the crop transpiration, manage the greenhouse irrigation and fertigation, and thus improve the cucumber yield.

Key words: Greenhouse, relative humidity, solar radiation, VPD, transpiration, temperature

Vapour pressure deficit (VPD) is considered as an important factor affecting the plant growth and development under greenhouse conditions. It is mainly governed by T_{apc} , E_{apc} and I_{rad} inside a greenhouse (Singh *et al.*, 2017; Singh *et al.*, 2018). It affects the crop transpiration inside greenhouse (Jolliet and Bailey, 1992) and thus the irrigation control. Under low VPD, transpiration rate from plants is also lower. While under high VPD, plants contribute to higher transpiration rates and greater water stress. The increased VPD in relation to higher temperature works against the effect of stomatal closure, when CO_2 enrichment is done (Nederhoff *et al.*, 1992). The elevated VPD values can hamper the photosynthesis, the plant growth, dry-matter accumulation and ultimately the crop yield (Deiveegan *et al.*, 2019). The fruit yield of cucumber reduces with increased VPD in relation to higher E_{apc} (Bakker, 1991). According to Singh *et al.* (2017), VPD values from 0.53 to 1.10 kPa are most favorable for optimal plant growth and fruit development

of cucumber. Thus, VPD can be used as a tool to maintain the greenhouse crop transpiration to an optimal range for obtaining maximum crop yield (Srivastava *et al.*, 2010; Kumar *et al.*, 2019).

Transpiration plays a significant role in irrigation management under protected conditions. It is related to VPD (even for values ≥ 2.5 kPa) in linear trend (Medrano *et al.*, 2005; Singh *et al.*, 2017). The higher transpiration rate, chiefly under hot climatic conditions appreciably increases the plant water requirements. The knowledge of crop transpiration may possibly aid to advance the irrigation management of soilless cultivation under protected structures (Medrano *et al.*, 2005). Transpiration is directly dependent on solar radiation reaching above the plant community. It has been considered as one of the important components of energy balance of a plant. The development of plants is directly connected to the water availability to them either in the plant tissues or as water

vapour in the air. Thus, it becomes imperative to monitor and control water application in greenhouse crops, water uptake by plant root system, internal water transport and the external transfer through transpiration. The present investigation was undertaken to study the trend in VPD via developing a computer module and its effect on crop transpiration of soilless cucumber in relation to subjected greenhouse microclimatic conditions.

MATERIALS AND METHODS

Experimental description

Cucumbers were cultivated in soilless media (coco-peat) inside a naturally ventilated greenhouse located at the Research Farm of Department of Soil and Water Engineering, Punjab Agricultural University, Ludhiana. The study site is located between latitude of 30° 56' N and longitude of 75° 52' E with an altitude of 247.0 m above mean sea level. The entire surface area of the greenhouse floor was covered with a mat for avoidance of weed emergence. Cucumbers were cultivated for two growing seasons *viz.* season 1: September 2016 to January 2017 and season 2: February to May 2017. The nursery of cucumbers was raised under a poly net house for two successive seasons. The vertically trained plants (through the strings attached to roller hooks with overhead wire) were nourished with nutrient solution on daily basis for a pre-decided time. The web based computer module for easy depiction of VPD through generation of charts was developed in the Department of Electrical Engineering and Information Technology, College of Agricultural Engineering, PAU Ludhiana. The greenhouse under experimentation has been described in Table 1.

Data recording and computation

The weather data on solar radiation, temperature and relative humidity both inside and outside the greenhouse under experimentation were recorded using the sensors through data logger (Table 2). The computed VPD was compared with the values obtained using the formula reported in Arellano *et al.* (2006). The crop transpiration was calculated using the equation derived from Penman-Monteith equation as reported in Medrano *et al.* (2005) with certain modifications in coefficients.

Computer module for VPD calculations under greenhouse conditions

A web based computer module for assisting in the basic calculation of vapour pressure deficit using the formulas given in Table 3 was developed. This module also included sub-module for uploading CSV file for data input in bulk and generate graphical representation in the form of Excel Chart for easy depiction (Fig.1).

The technology used in development of this module includes the followings:

- FrontEnd (HTML, CSS, JavaScript)
- Frameworks [jQuery(A javascript Framework), CanvasJS (A javascript Chart Library) and Bootstrap Framework(Styling HTML Elements)]
- BackEnd (PHP, MySQL)

RESULTS AND DISCUSSION

VPD behaviour

The Fig. 2 and 3 demonstrate the variation of VPD deficit computed by the developed module and its comparison with Singh *et al.* (2018) and Arellano *et al.* (2006). During season 1, the diurnal VPD was decreasing in trend with progress of the growing season. For example, on dates *viz.* 10th October 2016, 10th November 2016 and 10th December 2016, the VPD was computed to be in the range of 0.03 - 1.45 kPa, 0.01 - 0.79 kPa and 0.01 - 1.27 kPa, respectively having upper limits between 13:00 hr to 16:00 hr on daily basis (Fig. 4). A significant decrease in daytime VPD was observed between 10th October and 10th November, 2016. However, between 10th November and 10th December 2016, the VPD first decreased from 09:00 hr to 11:00 hr and then increased from 11:00 hr to 05:00 hr due to variations in outside weather conditions. VPD was computed to be maximum at maximum temperature and with minimum relative humidity.

During season 2 in 2017, VPD augmented rapidly with advancement in the growth season, particularly from Mid-March onward, chiefly due to increased temperature and decreased relative humidity. For example, on dates *viz.* 1st March 2017, 1st April, 2017 and 1st May 2017, the VPD was computed to be in the range of 0.01 - 2.74

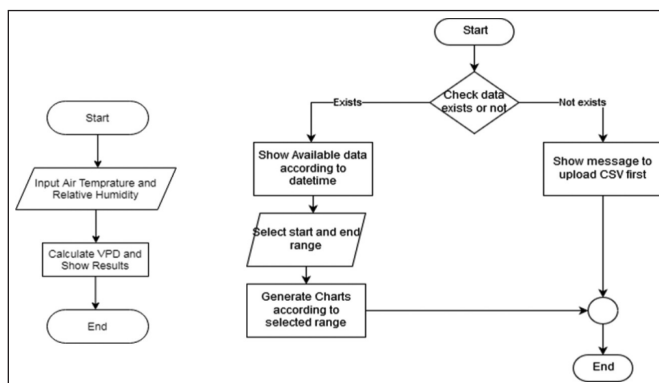
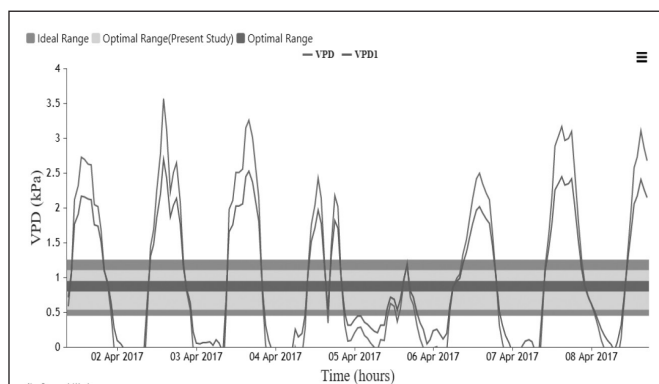
Table 1: Description of the greenhouse under experimentation

Greenhouse features	
Greenhouse type	Naturally ventilated greenhouse
North-South dimension (m)	28.0
East-West dimension (m)	20.0
Floor area of greenhouse (m ²)	560.0
Orientation of greenhouse	North-South
Covering material of greenhouse	UV stabilized polyethylene
Thickness of cover (μm)	200.0
Number of spans	02
Slope given to the greenhouse floor	1.0% (North-South)
Gutter height (m)	4.5
Ridge height (m)	6.5
Average transmissivity of cover	69.0%
Heating system used	None
Type of ventilation used	Natural
Insect net used for natural ventilation	40.0 mesh insect- net
Side ventilation (natural) area	20.0% (adjustable)
Fixed top ventilation (natural) area	10.0% (fixed)
Height at which foggers were installed	2.0 m above floor
Height at which shade net is installed	2.8 m above floor
Area under shade net (m ²)	384.0

kPa, 0.02 - 2.79 kPa and 0.26 - 4.55 kPa, respectively having upper limits between 13:00 to 14:00 hr (Fig. 1). The increased VPD with the progress of growing season 2 significantly affected the plant growth and requirement of nutrient solution through its direct relationship with crop transpiration. The VPD in the range of 0.53-1.10 kPa was recorded to be suitable for optimal plant development (Table 4).

Effect of T_{apc} , E_{apc} and I_{rad} on VPD

VPD was observed to be related linearly to T_{apc} and E_{apc} , while non-linearly to solar radiation throughout the crop growth period (Fig. 5 and 6). VPD increased ($R^2=0.85$) with T_{apc} and decreased linearly ($R^2=0.99$) with E_{apc} . For example, on 01.01.2017 (Fig. 5a), the highest value of VPD (1.44 kPa) was computed to be at 23.4°C (T_{apc}), 55.9 per cent (E_{apc}) and 0.0612 kWm⁻² (I_{rad}). Even in the absence of the crop (Fig. 5b), the trend was similar for VPD with respect to T_{apc} , E_{apc} and I_{rad} for a duration of 24 hours (diurnal variation) having R^2 values of 0.90, 0.99

**Fig. 1:** Data flow diagram and generation of charts**Fig. 2:** Graphical representation of VPD (through module)

and 0.69, respectively. However, the maximum value of VPD (1.09 kPa) was attained at 21.5°C (T_{apc}), 60.4 per cent (E_{apc}) and 0.073 kWm⁻² (I_{rad}).

Transpiration

The transpiration rate was directly affected by the solar intensity; T_{apc} and day time (Fig. 7). During season 1 of 2016, the transpiration from crop increased with increasing plant canopy area and ultimately decreased as a result of decreased T_{apc} with the progress of the season. For example, on dates *viz.* 27th December 2016 and 8th January 2017, the highest transpiration value was obtained to be 186.5 gm⁻²hr⁻¹ and 150.7 gm⁻²hr⁻¹ at 02:00 hr and 01:00 hr, respectively. While, during season of 2017, the transpiration augmented rapidly with advancement in the season in relation to mounting T_{apc} . For example, on dates *viz.* 23rd March 2017, 13th April 2017 and 4th May 2017, the maximum value of transpiration was computed to be 55.80, 305.10 and 423.60 gm⁻²hr⁻¹ at 11:00, 02:00

Table 3: Computation of VPD, transpiration and stomatal conductance or resistance

Parameter computation and method used	Reference/Availability	Equations (models) used
Module - VPD vs VPD1 - VPD vs VPD' - VPD - VPD' Micrfosoft excel	http://vpd.agromet-advisories.in	$VPD = 0.7392 \times \left(1 - \frac{E_{apc}}{100}\right) \times \exp(0.058 \times T_{apc})$ <p>Where, T_{apc}= temperature of air (°C) and E_{apc}= relative humidity in plant canopy (%)</p>
		$VPD' = 0.7392 \times \exp\{0.06264 \times T_{aos} \times \exp(-0.0019 \times t)\} - 0.8427 \times \frac{(E_{aos})}{100} \times \exp(0.06264 \times T_{aos} \times \exp(-0.8427 \times t) - 0.00021 \times t)$ <p>Where, T_{aos} = diurnal outside air temperature corresponding to time t, E_{aos} = diurnal relative humidity (%) of outside air corresponding to time t. 0, 1, 2, 3, 4,.....23 hours</p>
		$VPD1 = 0.61078 \times \exp\left(\frac{17.269 \times T_{apc}}{T + 237.3}\right) \times \left(1 - \frac{E_{apc}}{100}\right)$ <p>(Arellano <i>et al.</i>, 2006) T_{apc} = air temperature (°C) E_{apc} = relative humidity (%)</p>
Crop tranpiration	Medrano <i>et al.</i> , 2005	$T = \frac{A \times (1 - e^{-k \times LAI}) \times I_{rad} + B \times LAI \times VPD}{\lambda}$ <p>Where, T = transpiration ($\text{kg m}^{-2} \text{s}^{-1}$), I_{rad} = radiation (W m^{-2}), VPD = vapour pressure deficit (kPa), k = extinction coefficient, LAI = leaf area index ($\text{m}^2 \text{m}^{-2}$), λ = latent heat of vaporization of water (J kg^{-1}), A = equation parameter (dimensionless) and B = equation parameter ($\text{W m}^{-2} \text{kPa}^{-1}$). $LAI \leq 2.7$</p>

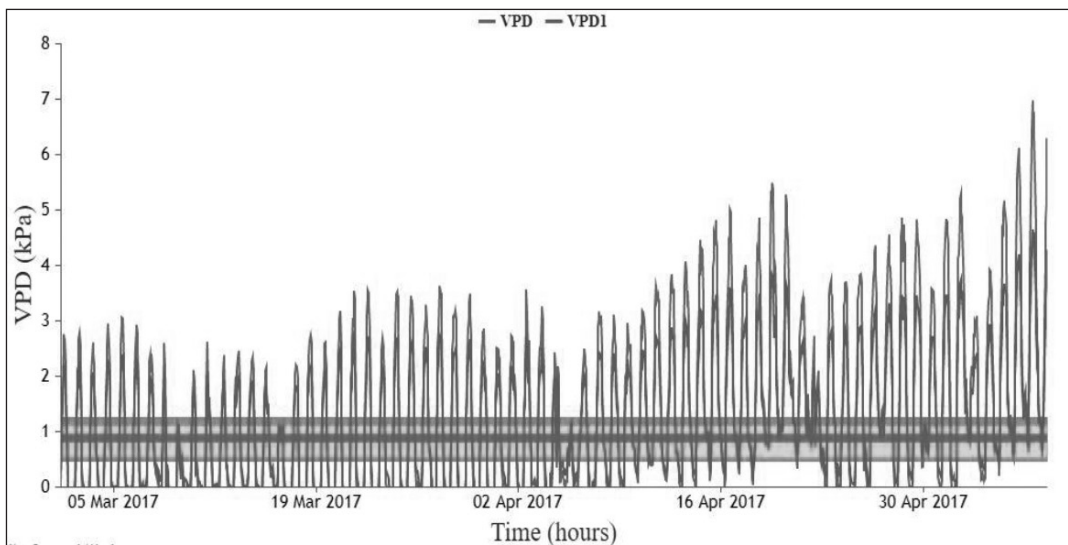


Fig. 3: Graphical representation of VPD for season 2 (through module)

and 15:00 hr, respectively.

Variation of transpiration with VPD

Transpiration increased linearly with VPD and vice-versa. Transpiration was also a function of LAI and increased with increasing LAI. Both transpiration and VPD were computed to be highest during day solar hours, generally between 12:00 hr and 03:00 hr. For example, on dates *viz.*, 1st March 2017, 1st April 2017 and 1st May 2017, the maximum and minimum values of transpiration and VPD were computed to be 207.1, 224.9 and 328.1 $\text{gm}^{-2} \text{hr}^{-1}$ and 2.7, 2.8 and 4.5 kPa, respectively (Fig. 8).

Transpiration was highly correlated with VPD in each case ($R^2 \geq 0.95$).

A strong linear positive relationship existed between VPD and crop transpiration (Fig. 5). At higher VPD, transpiration became unlimited due to increased evaporative demand and resulted in drying out of the plants. However, at lower VPD, transpiration was limited. During this study period, both T_{apc} and E_{apc} were significantly affected with operation of thermal shade net/screen, which in turn affected VPD and transpiration, and hence the crop water or nutrient requirement. The drop or

Table 4: Optimal range of climatic parameters for greenhouse cucumber cultivation

Parameter	Desirable range		
	Present study	Literature	
T_{apc} (°C)	22.0-27.0	Day: 23.9-26.7°C Night: 21.1-23.9 °C	Johnson and Hickman 1984
E_{apc} (%)	60.0-85.0	-	-
I_{rad} (kWm ⁻²)	0.100-0.169	-	-
VPD (kPa)	0.53-1.10	Between 0.8 and 0.95 (Ideal range, 0.45-1.25)	Anon (2017c)

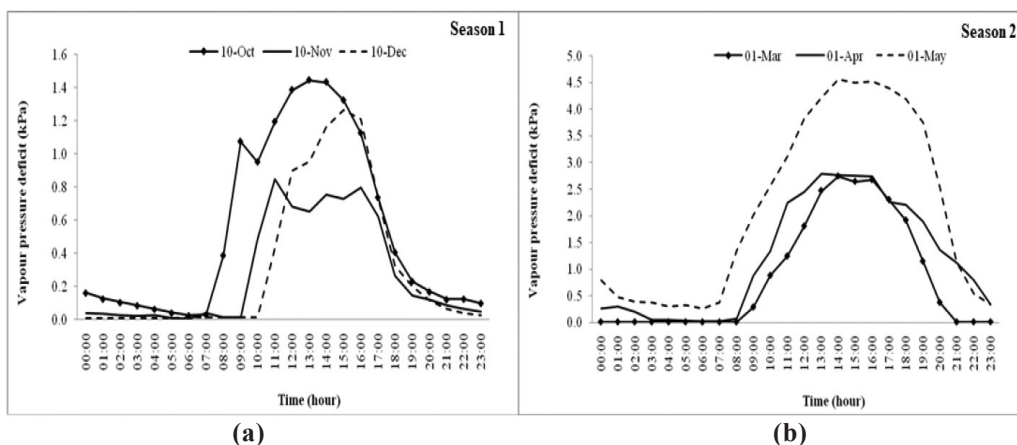


Fig. 4: Diurnal variation in VPD during a) season 1 and b) season 2 (Singh *et al* 2017)

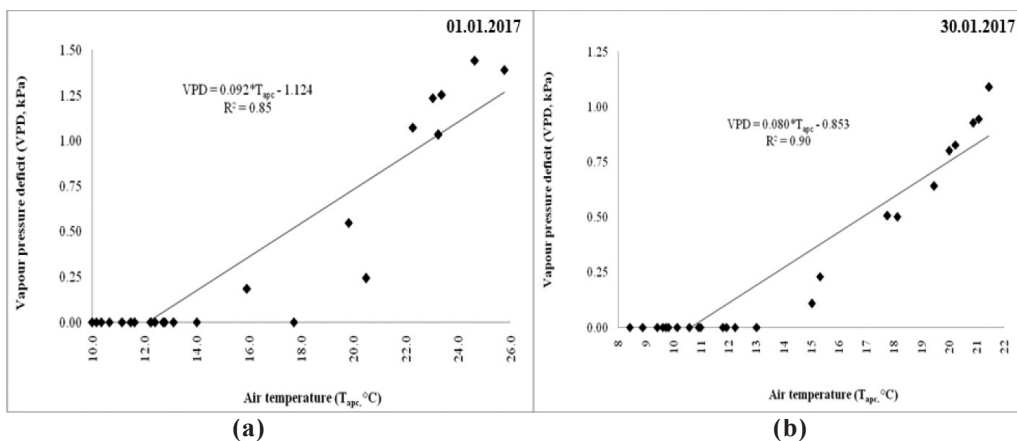


Fig. 5: Variation of vapour pressure VPD with T_{apc} on a) 01.01.2017 and b) 30.01.2017

rise in VPD was also found as a function of ventilation rate (side natural ventilation), which significantly affected the T_{apc} and E_{apc} inside of the greenhouse. VPD of air in the plant community increased due to increase in rate of air exchange through natural ventilation. A similar observation has also been reported in Jolliet and Bailey (1992). The cucumber yield was affected with variation in VPD and thereby the transpiration in relation to fluctuation in T_{apc} and E_{apc} . Similar effect of VPD and

crop transpiration on crop yield has been reported in El-Aidy (1990) and Sumathi *et al.* (2008). The operation of thermal shade net and natural ventilation rate had a significant effect on greenhouse microclimate (mainly on I_{rad} , T_{apc} and E_{apc}) and indirectly on VPD and crop transpiration. I_{apc} , T_{apc} and E_{apc} had a significant effect on VPD and the crop transpiration. Apart from using shade screen, the lower values of solar radiation (low light) inside the greenhouse were sometimes due to cloudy

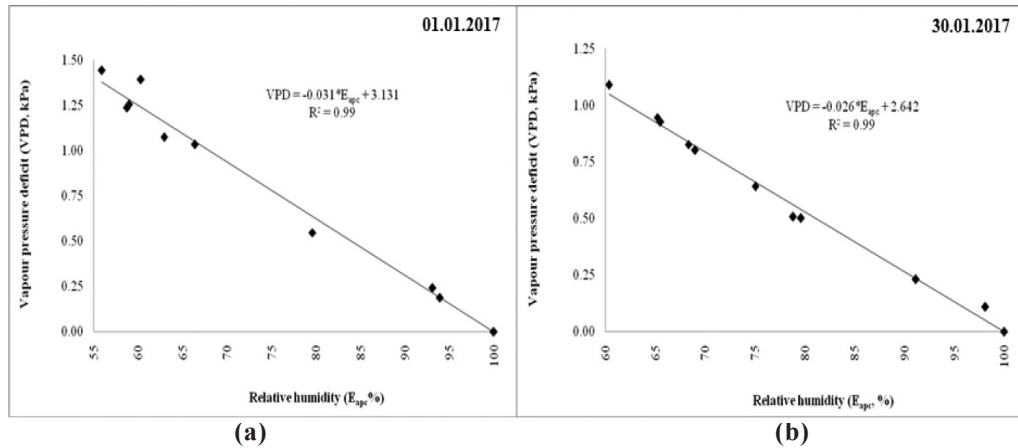


Fig. 6: Variation of VPD with E_{apc} on a) 01.01.2017 and b) 30.01.2017

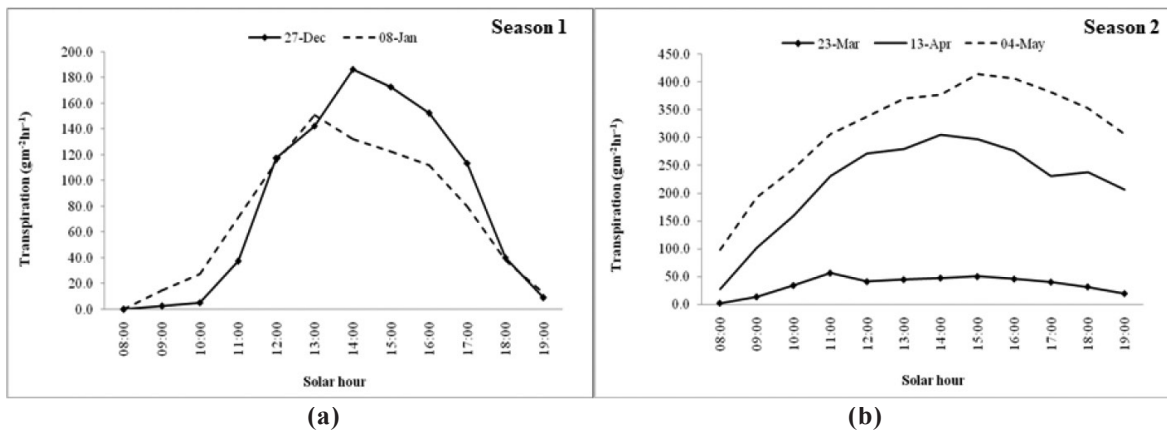


Fig. 7: Diurnal variation of crop transpiration during season 1 and season 2

weather conditions too.

The extremely low values of day time E_{apc} of greenhouse air encouraged the supply of nutrient solution to the crop. Similar effect of low E_{apc} has also been discussed in Yang *et al.* (1989). In the present study, the optimal range of T_{apc} , E_{apc} , I_{rad} and VPD were projected based on microclimate modeling (Table 4). Fig. 5 indicates a linear relationship between transpiration and VPD. Such relationship between VPD and crop transpiration has already been reported in past (Medrano *et al.*, 2005). Transpiration varied linearly with VPD even for values higher than 3.5 kPa and such variation in crop transpiration with VPD has also been reported in Medrano *et al.* (2005). Further, the transpiration was the factor considered for fertigation scheduling, which can be helpful in improving irrigation management in crops grown in soilless media under polyhouse conditions (De

Boodt and Verdonck, 1972). Apart from this, there exists a relationship between VPD and transpiration in relation to prevailing climatic conditions such as wind speed and rate of ventilation.

CONCLUSIONS

The VPD indicated an increasing trend with T_{apc} ($R^2 \geq 0.84$) and decreasing trend with E_{apc} ($R^2 = 0.99$) with a strong positive correlation. Crop transpiration in relation to VPD was significantly affected by T_{apc} , E_{apc} and I_{rad} . The increasing crop transpiration with VPD, mainly during hot climatic conditions significantly increased the water input or fertilizer (nutrient solution) use in soilless cultivation systems. Thus, transpiration in relation to VPD should be considered as a factor for fertigation scheduling and improving irrigation control in soilless systems. Moreover, maintaining T_{apc} , E_{apc} and VPD within range of

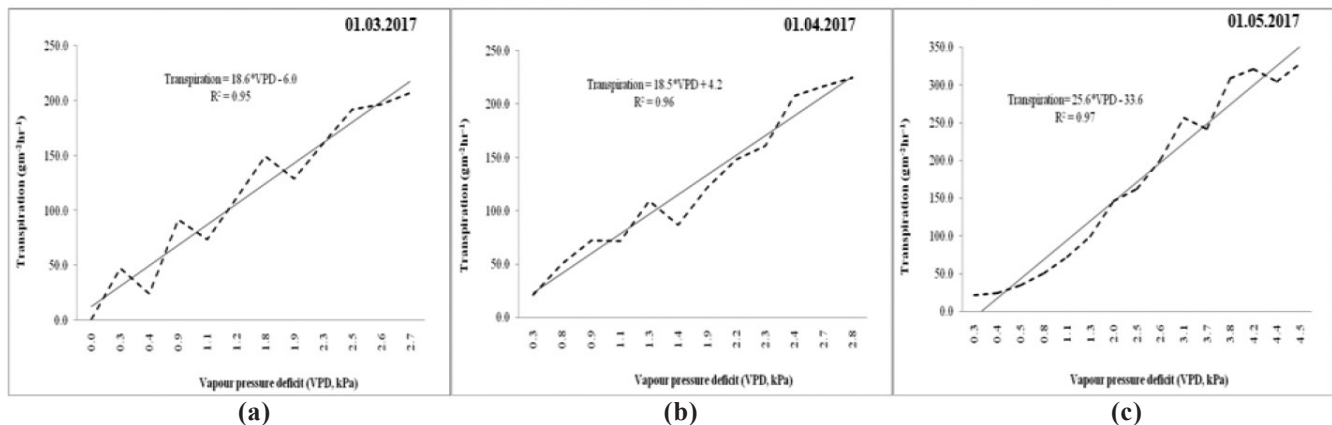


Fig. 8: Variation of transpiration with VPD on a) 01.03.202017, b) 01.04.17 & c) 01.05.2017

22-27°C, 60-80 per cent and 0.53-1.10 kPa, respectively may help to control the crop transpiration, manage the greenhouse irrigation and fertigation, and thus improve the cucumber yield. Furthermore, the developed web based computer module can be successfully utilized for generating graphical representation of VPD in the form of Excel Chart for its easy depiction.

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