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Development of mathematical models for predicting vapour pressure deficit inside a greenhouse from internal and external climate

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ABSTRACT

Vapour pressure deficit (*VPD*) inside protective structures under cropped conditions significantly affects the plant growth and productivity through its direct relationship with crop transpiration or irrigation management. Thus, monitoring *VPD* inside greenhouse during crop growth period becomes essential to limit it to a desired range. The present study was undertaken to develop mathematical models for predicting *SVP*, *AVP* and *VPD* inside a greenhouse independently using internal and external climatic parameters as inputs. The root mean square error (*RMSE*) was obtained in the range of 0.03-0.10 kPa and 0.27-1.03 kPa respectively for the models developed from internal and external climatic parameters as model inputs. The average model efficiency (n_{eff}) was computed to be 98.7 per cent, 92.2 per cent and 100.0 per cent respectively for *SVP*, *AVP* and *VPD* when predictions were made using internal climate as input. Similarly, for the models developed from external climate as model input, n_{eff} was worked out to be 96.7, 86.1 and 93.0 per cent for *SVP*, *AVP* and *VPD* respectively. The developed models presented a high degree of precision in predicting *SVP*, *AVP* and *VPD* with both internal and external climatic conditions as model inputs inside a naturally ventilated greenhouse under cucumber crop in soilless media.

Keywords: *Greenhouse, MATLAB, modeling, simulink,* VPD

Vapour pressure deficit (*VPD*) and leaf area index (LAI) are two key parameters which affect the greenhouse crop transpiration (Singh *et al*., 2017a) thereby the crop water requirement and productivity. Annu Priya *et al.* (2014) reported that increase in vapour pressure deficit resulted in increase in ET_o during different seasons at Varanasi. The *VPD* between greenhouse air and crop affects the transpiration and accordingly the absolute air humidity. *VPD* under cucumber crop in soilless culture is linearly related to transpiration even for higher values (>3.0 kPa) (Singh *et al*., 2017b). *VPD* negatively affects the mean fruit weight of cucumber with an increase in *VPD* under high relative humidity. According to Singh *et al* (2017b), *VPD* should lie in the range of 0.53-1.10 kPa for best possible growth and development of cucumber plant. Only a trivial effort has been made to model the vapour pressure (or *VPD*) inside a greenhouse under cucumber crop in soilless media. The present study was thus undertaken to develop mathematical models for predicting *SVP*, *AVP* and *VPD* inside a naturally ventilated greenhouse when cucumber crop was cultivated in soilless media separately from internal and external climate.

MATERIALS AND METHODS

Description of study site

Experimental trials were carried out inside a 28.0 m×20.0 m (floor area 560.0 m^2) double-span naturally ventilated greenhouse oriented in North-South direction at Punjab Agricultural University, Ludhiana (latitude: 30° 56′ N, longitude: 75° 52′ E and altitude: 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 in coco-peat growing media inside the greenhouse for two growing seasons

Season 1: September 2016 to January 2017 and

Season 2: February to May 2017.

Cucumber plants were trained vertically by means of string attached to the roller hooks and fertigated with nutrient solution on daily basis for a predetermined time. The greenhouse was facilitated with natural ventilation (four sides and top), a thermal shade net for shading and foggers for evaporative cooling. The area under natural ventilation was 30.0 per cent (10.0% from top and 20.0% from sides). Foggers and shade net were installed at a height of 2.0 m and 2.8 m height with respect to greenhouse floor.

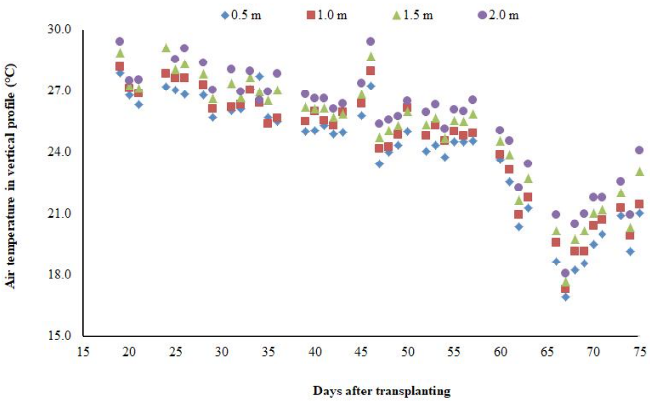

Fig. 1: Variation in air temperature vertically up in plant community during (September 2016 to January 2017)

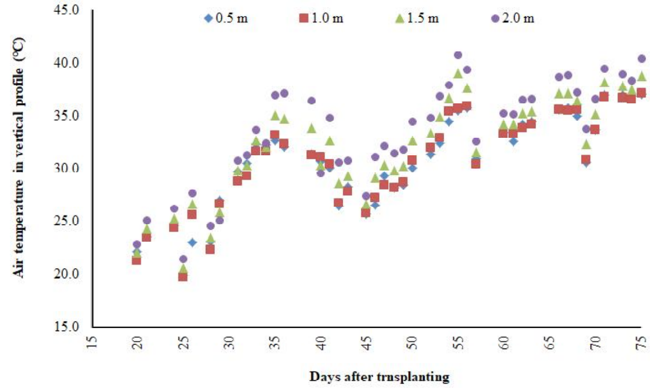

Fig. 2: Variation in air temperature vertically up in plant community during (February 2017 to May 2017)

The height of greenhouse at centre and gutter was 6.0 m and 4.0 m respectively.

Measurement of dynamic parameters

The temperature and humidity sensors were installed (inside and outside the greenhouse) at an average height of 1.84 m in the plant community. The diurnal climatic data (temperature and humidity) was logged in the data logger (Delta-T Devices, UK) installed inside the greenhouse separately from inside and outside the greenhouse at an hourly interval on daily basis. Using the recorded data, the *VPD* and *SVP* inside the greenhouse were computed using methods reported in Arellano *et al*. (2006) and Sengar and Kothari (2008) respectively.

Model development with internal climate as input

Saturation vapour pressure (SVP)

The vapour pressure indicates the evaporation rate of a liquid at a given temperature. In a closed system at a particular temperature, vapour pressure (or equilibrium vapour pressure) is the pressure exerted by a vapour in ther modynamic equilibrium with its solid or liquid phase. *SVP* is dependent on temperature and material under consideration. The observed data was analyzed critically through curve fitting and multiple regression analysis to form mathematical relationship between SVP and temperature. Mathematically, the developed model is given as.

$$SVP = A \times e^{B \times T_{apc}} \tag{1}$$

The slope of *SVP* versus temperature curve is given by following equation.

$$\text{Slope}\,(m) = \tan\theta = \frac{dP_s}{dT_{apc}} = 0.058 \times SVP \tag{2}$$

Where, θ is the angle made by the tangent to the *SVP* versus temperature curve with horizontal surface.

Actual vapour pressure (AVP)

The *AVP* is dependent on relative humidity and temperature.

$$AVP = A \times \left(\frac{E_{apc}}{100}\right) \times e^{B \times T_{apc}} \tag{3}$$

Vapour pressure deficit (VPD)

The *VPD* was obtained by difference between *SVP* and *AVP*

$$VPD = A \times \left(1 - \frac{E_{apc}}{100}\right) \times e^{B \times T_{apc}} \tag{4}$$

Where, T_{apc} is air temperature in plant community (°C), E_{apc} is relative humidity in plant community (%), *A* (0.7392) and *B* (0.058) are empirical coefficients.

Model development with external climate and time as inputs

Saturation vapour pressure (SVP)

$$SVP = P \times \exp\left\{Q \times T_{aos} \times \exp\left(-R \times t\right)\right\} \tag{5}$$

Actual vapour pressure (AVP)

$$AVP = S \times \frac{(E_{aos})_i}{100} \times \exp(Q \times T_{aos} \times \exp(-R \times t) - T \times t) \tag{6}$$

Vapour pressure deficit (VPD)

$$\text{VPD} = P \times \exp\left\{Q \times T_{aos} \times \exp\left(-R \times t\right)\right\}$$
$$S \times \frac{(E_{aos})_i}{100} \times \exp(Q \times T_{aos} \times \exp(-R \times t) - T \times t) \tag{7}$$

Where, T_{aos} is outside air temperature, E_{apc} is relative humidity (%) of outside air at time *t*, *t* (0,1, 2, 3…) is the time (hour). *P, Q, R, S* and *T* are empirical coefficients such that *P*= 0.7392, *Q* = 0.06264, *R* = 0.0019, *S* = 0.8427 and *T* =

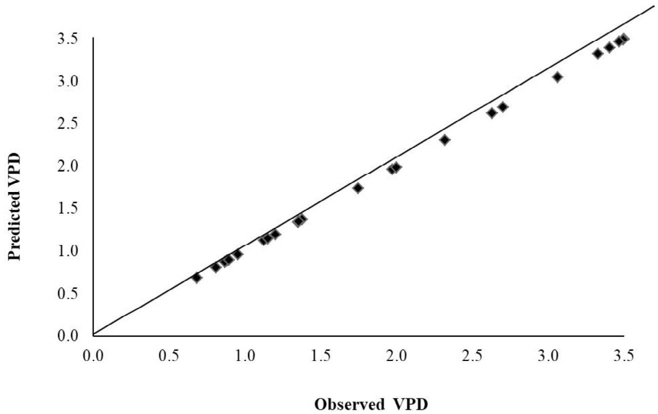

Fig. 3: Relationship between predicted and observed VPD using internal climatic data as model input during (April 2017)

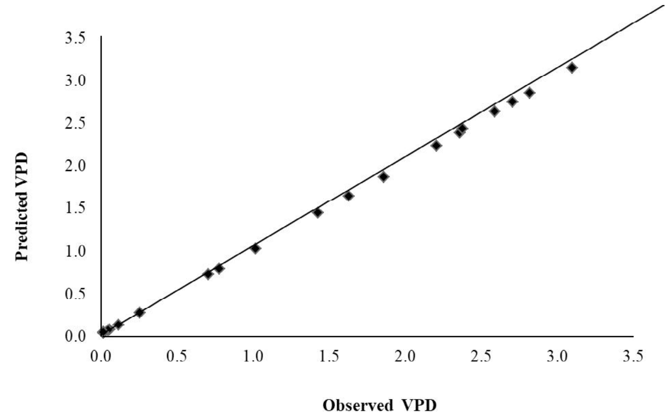

Fig. 4: Relationship between predicted and observed VPD using external climatic data as model input during (April 2017)

Table 1: Statistical analysis

Parameter	Modeled from Internal climate			Modeled from external climate		
	VPD	*SVP*	*AVP*	*VPD*	*SVP*	*AVP*
σ_{obs}	0.41-1.31	0.50-1.67	0.15-0.52	1.41-2.91	3.41-4.86	1.98-2.24
σ_{pre}	0.41-1.34	0.48-1.23	0.14-0.55	1.29-3.52	3.12-4.54	1.16-1.97
RMSE	0.00-0.04	0.03-0.10	0.03-0.09	0.27-0.85	0.41-0.97	0.31-1.03
R^2	0.99-1.0	0.99-1.0	0.99-1.00	0.91-0.97	0.98-0.99	0.86-0.99
n_{eff}	99.99-100.0	97.4-99.9	86.3-98.1	88.9-97.0	94.4-99.0	74.0-98.1

Where, σ_{obs} = observed or computed standard deviation, σ_{pre} = predicted standard deviation, R^2= coefficient of determination, *RMSE* = root mean square error and n_{eff} = model efficiency.

0.00021. The above equations (equations 7, 8 and 9) can be used to predict *SVP*, *AVP* and *VPD* from external climate (temperature and humidity) and time as inputs.

Statistical analysis

The statistical parameters viz. standard deviation (σ), coefficient of determination (R^2), root mean square error (*RMSE*) and model efficiency (n_{eff}) were estimated to evaluate the performance of developed models (Table 1). The model efficiency was calculated using equation given by Nash and Sutcliffe (1970).

RESULTS AND DISCUSSION

Variation of temperature in the plant community

Air temperature in plant community (T_{apc}) was certainly affected with height in plant community during both cropping seasons (Fig. 1 and 2). During season 1 (Sept.'16 to Jan.'17), the average rise in air temperature was recorded in the range of 22.9-24.6 °C from 0.5 m to 1.8 m height. Similarly, during season 2 (Feb. to May'17), the average rise in air temperature was found in the range of 30.9-33.5 °C with height from 0.5 m to 1.8 m height. It is therefore important to train the plant to an optimum height in relation to the temperature variation in the vertical profile in greenhouses, especially during summer.

Model validation from internal climate

The models were validated through comparison between the actual and predicted data of *SVP*, *AVP* and *VPD* for selected period i.e. during 28th December 2016 to 2nd January 2017. The statistical parameters estimated for evaluation of model performance are presented in Table 1. The developed model of *VPD* was validated for a period of six days from December 28, 2016 to January 02, 2017 during season 1.

For the air temperature in plant community, the mean standard deviation for observed and predicted data was 4.4°C and 5.1°C respectively. The average root mean square error (*RMSE*), coefficient of determination (R^2) and model efficiency (n_{eff}) were computed to be 1.7 °C, 0.95 and 88.3 per cent respectively. However, for relative humidity of air within plant community, the mean standard deviations for observed and predicted data were 20.7 per cent and 21.3 per cent respectively. *RMSE*, R^2 and n_{eff} were obtained as 8.8, 0.95 and 81.7 per cent respectively.

During season 2, the developed model of *VPD* was also validated for a period of six days from March 28, 2017 to April 02, 2017. For *VPD,* the mean standard deviation for actual and predicted data was 0.86 and 0.88 kPa respectively. The average *RMSE*, R^2 and n_{eff} were computed to be 0.02 kPa, 1.0 and 100.0 per cent respectively. For *SVP,* the mean standard deviation for actual and predicted data was 1.09 and 0.86 kPa respectively. The average *RMSE*, R^2 and n_{eff} were obtained to be 0.07 kPa, 1.0 and 98.7 per cent respectively (Table 1).

Model validation from external climate

The developed models were validated for diurnal variation in *SVP*, *AVP* and *VPD* through a comparison between the actual and predicted data. Fig. 3 and 4 demonstrate the relationship between predicted and actual data VPD for the models developed to make predictions using internal and external climatic data as model inputs during season 1 and 2 respectively. For *VPD*, the mean standard deviation for observed and predicted data was computed as 2.16 and 2.41 kPa respectively. The average *RMSE*, R^2 and n_{eff} were 0.56 kPa, 0.94 and 93.0 per cent respectively.

For *SVP* the mean standard deviations for observed and predicted data were 4.14 and 3.83 kPa respectively. The average *RMSE*, R^2 and n_{eff} were computed to be 0.69 kPa, 0.99 and 96.7 per cent respectively. For *AVP* the mean standard deviations for observed and predicted data were 2.11 and 1.57 kPa respectively. The average *RMSE*, R^2 and n_{eff} were obtained to be 0.67 kPa, 0.93 and 86.1% respectively.

The statistical analysis of simulation results of the model as shown in Table 1 indicated that the above models can be applied at any compartment of heated (naturally) or unheated greenhouses, may or may not provide with natural ventilation. However, variation may arise with respect to time and regional climatic conditions.

CONCLUSIONS

Having known the importance of *VPD* for plant growth and productivity under a protective structure, models were developed for predicting *SVP*, *AVP* and *VPD* independently with internal and external climatic parameters as model inputs. The statistical comparisons indicated that the developed models were sufficiently accurate to simulate the *SVP*, *AVP* and *VPD*. Thus, the developed models can be adopted to predict the *SVP*, *AVP* and *VPD* inside a greenhouse under cropped conditions independently with internal and external climatic conditions as model inputs.

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