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Development of a microclimate model for prediction of temperatures inside a naturally ventilated greenhouse under cucumber crop in soilless media

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ABSTRACT

The microclimate inside a protected structure is affected mainly by physical processes involving heat and mass transfer between plants, air, growing media and the plastic cover. The microclimate within plant community directly affects the plant metabolic activities and therefore the production. Thus, it becomes imperative to monitor and maintain the microclimatic parameters to desired range for optimal plant growth and development. A microclimatic model of a naturally ventilated greenhouse under cucumber crop in soilless media was developed by considering the heat or mass transport processes (convection, radiation, transpiration and natural ventilation) and solved in Simulink MATLAB. The model performance was evaluated statistically through a comparison between predicted and observed data. The averaged absolute percent error for temperature of air, plant, growing media and was computed to be 8.9%, 7.6%, 8.0% and 10.6% respectively. The coefficient of determination (r^2), root mean square error (*RMSE*) and model efficiency (η_{eff}) were obtained to be 0.96, 0.11 °C and 94.7% respectively. The statistical comparisons indicated that the developed microclimate model was sufficiently accurate to predict the temperature at air, plant (leaf), growing media and greenhouse cover under cropped conditions inside a naturally ventilated greenhouse. However, some model coefficients may require adjustments with respect to change in crop type and greenhouse conditions. The model output would be helpful in monitoring and offering optimal plant growth conditions which in turn can help in irrigation and fertigation management of the crop grown.

1. Introduction

The assembly of climatic parameters forming around a living plant is termed as microclimate (Bailey, 1985). It is the greenhouse microclimate that directly affects plant metabolic activities and therefore the crop yield (Singh et al., 2018c). The microclimate of a greenhouse is a combination of physical processes involving heat and mass transfer which are governed by environmental conditions, type of structure, state of crop grown and effect of control actuators (Bot, 1983). The internal climate of a protected structure is strongly dependent on outside climatic conditions, especially under unheated conditions. Light (Wilson et al., 1992), temperature and relative humidity are the key parameters which significantly affect the crop development, yield and fruit quality. According to Sauser et al. (1998), the temperature distribution inside a protected structure influences the uniformity of crop growth. According to De Koning (1996), limiting temperature in desired range is essential for optimal crop growth. The root-zone temperature in relation to air temperature in plant community also significantly affects the plant development and flowering (Khah and Passam, 1992). Thus, the microclimate within the plant community under a protected structure should be according to the requirement of the crop grown (Singh et al., 2018a, 2018b). A better understanding of the relationship between greenhouse microclimate and plants is thus highly desirable (Singh et al., 2017a) to offer optimal plant growth conditions.

Under hot climatic conditions, the optimal plant growth environment can be maintained through ventilation, shading and fogging (evaporative cooling). Ventilation can be performed either mechanically or naturally through wind and buoyancy (Willits, 2003). Natural ventilation can help in dissipating surplus heat and vapour through exchange between inside and outside air, while it can exclude excessive vapour and provide a suitable thermal climate in winter (Baptista et al., 1999). Shading which favours the plant growth (Hashem et al., 2011) is another method of controlling greenhouse microclimate. When light intensity becomes too high within the plant community, shading can be performed (Stanghellini and Van Meurs, 1992). Furthermore, greenhouse cooling efficiency can be increased if evaporative cooling is combined with a reduced ventilation rate (Li et al., 2006).

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Modeling is a commonly used technique for quantification of greenhouse microclimate. Microclimate modeling has become essential to offer most favourable climatic conditions inside the greenhouses in different growth stages of plants (Sethi et al., 2013). The main objective of greenhouse microclimate modeling is to quantitatively describe the energy and mass transport processes by mechanism of conduction, convection and radiation. Energy balance equations can be used to construct models which permit prediction of greenhouse microclimate based on outside climatic conditions. Simulation models can be used for predicting the inside microclimate (Solar radiation, light intensity, air temperature, plant temperature, temperature of growing media, relative humidity, CO_2 concentration, vapour pressure deficit (VPD), etc.) as a function of greenhouse features and outside climatic conditions. Predicting microclimate inside a greenhouse can help growers to manage crop production and designers to improve the ventilation and heating systems.

1.1. History of model development

Between year 1970 and 2000 in 20th century, numerous models (static and dynamic) were developed to describe heat and mass transport processes in plant community under greenhouse conditions (Soribe and Curry, 1973; Tiwari, 1985; Alain, 1989; Yang et al., 1990b; Seki et al., 1995, Stanghellini and de Jong, 1995; Zhang et al., 1997; Gijzen et al., 1998; Tiwari et al., 1998; Teitel and Tanny, 1999) and validated for various climatic conditions under different crops. From year 2000 onward to till date in 21st century, several models of greenhouse microclimate have also been developed internationally (Zhang et al., 2002, 2005; Ghosal and Tiwari, 2004; Salgado and Cunha, 2005; Singh et al., 2006; Baptista et al., 2010; Fitz-Rodriguez et al., 2010; Chen et al., 2011; Vanthoor et al., 2011; Wang et al., 2014; Yang et al., 2016; Misra and Ghosh, 2017; Reyes-Rosas et al., 2017).

Kimball (1973) modeled conductive, radiative, sensible and latent heat fluxes at different locations in a greenhouse. He concluded the developed model as an efficient tool for predicting the heating and cooling requirements of a greenhouse for a wide range of greenhouse properties and environmental conditions. Avissar and Mahrer (1982) successfully designed and validated a one-dimensional numerical model to simulate the diurnal changes in greenhouse environment by dividing the greenhouse into four compartments viz. soil, vegetation, air and cover. Mahrer and Avissar (1984) modeled thermal radiative, conductive, sensible and latent heat fluxes to simulate the diurnal changes of the greenhouse environment. Their model successfully evaluated the heating or cooling requirements of glass and polyethylene covered greenhouses in the coastal region of Israel during the winter and summer seasons. Levit and Gaspar (1988) successfully developed and verified a one-dimensional dynamic computer model for simulating the greenhouse microclimate under different climatic conditions. Their model included crop thermal storage and time evolution of the crop characteristics. Yang et al. (1990b) successfully simulated the greenhouse microclimate using a dynamic greenhouse microclimate model developed by them for five major microclimatic variables viz. solar radiation, transpiration, leaf temperature, air temperature and relative humidity under cucumber crop.

Gonima (1992) proposed a model based on integration of the radiative transfer equations to calculate the long wave net radiation at the surface under all sky conditions. He proposed some simple empirical expressions for estimation of temperature, water vapour density and pressure profiles in order to simplify calculations of the long wave net radiation at the surface. Boulard and Baille (1993) efficiently predicted air temperature, humidity, crop temperature and transpiration using a greenhouse microclimate model. Their model incorporated the effects of natural ventilation and evaporative cooling on greenhouse microclimate. Jolliet (1994) presented a model to predict humidity and transpiration directly from outside climate with the objective to develop most favorable control strategies for humidity in greenhouses. His model accurately predicted the VPD, relative humidity, transpiration and condensation inside the greenhouse. Seki et al. (1995) developed a mathematical model to predict greenhouse microclimate for cucumber crop with the combination of population dynamics and transport process sub-model. Their model confirmed a fairly good prediction of plant community growth process, energy and mass transfer processes in the plant community. Zhang et al. (1997) presented a one-dimensional numerical model to predict the microclimate inside an unheated commercial greenhouse. The outputs of their model (hourly air temperature, leaf temperature and relative humidity) were used to derive the leaf wetness duration on daily basis.

Lorenzo et al. (1998) derived a multiple regression function from Penman-Monteith equation to compute crop transpiration by coupling a radiative term associated with radiation absorbed by crop and an advective term that included air VPD. Their model reported a linear relationship between crop transpiration and VPD even for higher values ($>$ 2.5 KPa). Sharma et al. (1999) performed a numerical analysis and experimental validation of a model for a typical winter day to study the effects of infiltration, heat capacity of plants, relative humidity and air temperature on greenhouse microclimate. Their study reported a significant effect of heat capacity of plant and relative humidity on plant temperature than air temperature with a fairly good agreement between the predicted and observed values. Teitel and Tanny (1999) successfully developed a theoretical model based on non-dimensional mass and energy conservation equations to simulate the transient response of the greenhouse air temperature and humidity to the opening of roof windows. According to them, the effect on ventilation increased significantly with the height of window opening and wind speed with decreased solar radiation. Boulard and Wang (2000) presented a new and simple greenhouse crop transpiration model for prediction from external climate. The performance of their model was satisfactory when the greenhouse air was closely coupled to the outdoor climatic conditions with an improvement in model estimations from spring to summer. Wang and Boulard (2000) efficiently simulated the microclimate of a naturally ventilated greenhouse using the gembloux greenhouse dynamic model (GGDM) and developed a linear non-dimensional ventilation function. Their study reported external wind speed and opening angle of the vents as the most important factors influencing the ventilation flux through sensitivity analysis.

Zhao et al. (2001) studied temperature and humidity distributions vertically under closed and naturally ventilated greenhouse conditions by comparing the ventilation through continuous roof openings only and combination of roof and side ventilation. Their study, reported smaller gradients with only roof ventilation than the combination of roof and side openings. Boulard and Wang (2002) studied the climate and crop transpiration distributions in a plastic greenhouse tunnel using computational fluid dynamic software jointly with a global solar radiation model and a crop heat exchange model. They successfully validated the model and predicted the transpiration flux of a mature lettuce crop. Zhang et al. (2002) developed and validated a dynamic one dimensional model (PSCLIMATE) to predict air temperature and relative humidity within the plant canopy of cucumber crop. Their model can be used for different crop canopies or greenhouse structures once the specific characteristics of the greenhouse structure and plant canopy are defined. Ghosal and Tiwari (2004) developed and validated a thermal model for heating of a greenhouse by using inner thermal curtain and natural flow of geothermal warm water through the polyethylene tube placed on its floor. The greenhouse was divided into three zones viz. zone I (plants under thermal blanket), zone II (space under ceiling) and zone III (space between roof and ceiling). Ghosal et al. (2004) developed a simplified analytical model to study the year round effectiveness of a recirculation type earth air heat exchanger coupled with a greenhouse. They evaluated the performance of the system in terms of thermal load leveling and coefficient of performance indicating a high accuracy between predicted and measured air temperatures.

Zhang et al. (2005) efficiently developed and validated a one-