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Greenhouse microclimate modeling under cropped conditions - A review

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Abstract: Growing vegetable crops in greenhouse conditions has become popular throughout the world. The greenhouse technology supports a favorable environment for crop growth and development. Greenhouse climate is the major driving force which directly affects the plant metabolic activities, fruit quality and therefore the production of crops. The greenhouse microclimate is a combination of physical processes involving energy and mass transfer processes which are governed by environmental conditions, greenhouse structure, crop type and state, and effect of the control actuators. Solar radiation, temperature distribution and relative humidity are the main microclimatic parameters needed to evaluate the climate suitability in a region for crop growth under protected cultivation. Numerous models have been developed in the past to describe the microclimate under different greenhouses and crops conditions. Still, there exists a scope for better understanding of the relationships between microclimate and plants community by means of appropriate modeling techniques. Here, we have made an attempt to review the greenhouse microclimate modeling studies during last few couple of decades.

Key words: Greenhouse, Microclimate, Modeling, Microclimatic parameters

Introduction

The greenhouse technology creates a favorable environment for cultivating desirable crops year round. A greenhouse traps the short wavelength solar radiation to create a favorable microclimate for higher crop productivity (Tiwari, 2006). The production of vegetable crops in greenhouse results in minimum use of chemical fertilizers and pesticides, which is not possible under open field conditions. Protected cultivation is now very much needed under Indian conditions to improve the quality and productivity of the vegetable crops (Kohli *et al.,* 2007). In the present scenario of perpetual demand of vegetables and shrinking land holdings drastically, protected cultivation is the best alternative and drudgery-less approach for using land and other resources more efficiently. The practice of protected cultivation of vegetable crops is also becoming popular in the hilly regions of the India, which offers a great scope for use of low cost naturally-ventilated polyhouses because of mild climate (Mishra *et al.,* 2010). In world, China has the largest area (2,760,000 hectares) under greenhouse cultivation followed by Korea having 57,444 hectares (Nair and Barche, 2014). In Europe, Spain is leading in protected agriculture with 51,000 ha mostly under low cost poly houses (Nair and Barche, 2014). In recent decades, the greenhouse area has risen worldwide, mainly due to the increased use of plastic greenhouses for growing vegetable crops. Mishra *et al* (2010) have reported about 110 ha in India and over 275,000 hectare in world under greenhouse cultivation by the end of 20th century. The area under greenhouse cultivation in Punjab is 20 ha out of 1.70 lakh ha under vegetable crops and Himachal Pradesh has 223.18 hectare under (Spehia, 2015). Maharashtra and Gujarat had a cumulative area of about 5,730 and 4,721 hectares respectively under the protected cultivation till 2012 (Nair and Barche, 2014).

Greenhouse microclimate and its importance: The assemblage of climatological parameters forming around living plants inside a greenhouse is termed as greenhouse microclimate. Greenhouse climate is the major driving force influencing fruit quality and productivity of greenhouse crops (Papadopoulos *et al*., 1997; van Henten *et al*., 2006). It is the greenhouse microclimate that directly affects the plant metabolic activities and therefore the production. The greenhouse microclimate is a combination of physical processes involving energy transfer (radiation and heat) and mass balance (water vapor fluctuation and CO_2 concentration). These processes are governed by environmental conditions, greenhouse structure, crop type and state, and effect of the control actuators (Bot, 1983). Keeping this in mind, Bailey (1985) has emphasized that a better understanding of the relationships between microclimate and plants is very important and desirable. It is much difficult to measure and monitor the greenhouse microclimate within the plant canopy and on the plant surface. The main reason for microclimate control in greenhouses is to achieve desirable plant growth and yield. The greenhouse microclimate may be controlled by controlling the heating system, ventilation and fogging system, lighting and shading system, fertigation system and CO_2 injection system. Differences occur between the microclimate around a leaf surface and the ambient air due to photosynthesis, transpiration and vapor condensation processes. These differences between plant microclimate and ambient conditions need to be understood quantitatively to predict more accurately the pest and disease outbreaks and improve the efficiency of their control measures.

Microclimate parameters: Solar radiation, temperature distribution (Sauser *et al.,* 1998) and relative humidity are the main climatic parameters needed to evaluate the climate suitability in a region for crop growth under protected cultivation. The other climate parameters such as soil temperature in relation to air temperature, wind, rainfall and air composition, influence to a lesser degree. Carbon dioxide (CO_2) and photosynthetically active radiation (PAR) accumulated over the day, are also two primary variables which affect the plant growth in a greenhouse. Water vapor pressure deficit (VPD) between greenhouse air and crop may affect the transpiration and consequently absolute air humidity. Cooling has always been an important problem for greenhouse operator in warm climates, potentially limiting production and constraining profits. Green house cooling is typically accomplished by ventilation, either mechanically or naturally by wind and buoyancy (Willits, 2003).

Greenhouse microclimate models and application: Modeling is a commonly used technique for quantification of greenhouse microclimate. The studies on greenhouse models have been carried internationally for many years (Yang *et al*., 1990; Zhang *et al*., 1997; Gijzen *et al*., 1998). Modeling of greenhouse microclimate is very important to maintain optimum inside environment during different stages of plant growth for desirable crop production. The main objective of greenhouse microclimate modeling is to quantitatively describe the energy and mass transport processes by mechanism of convection within the medium, the exchange processes between air and plant elements and other surfaces, and the ways in which plants respond to the environmental factors. Numerous models (static or dynamic) have been developed in the past for describing the greenhouse microclimate. Static models are used mainly to describe the thermal behavior of the greenhouse or to analyze the effect of environmental control techniques on the microclimate conditions (Bailey, 1981; Baille *et al*., 1985; Seginer *et al*., 1988). Dynamic models are equally important for simulating the greenhouse response on a small timescale, which requires the proper representation of the heat exchange processes. Numerous researchers have developed complex (Zhang *et al*., 1997; Wang and Boulard, 2000; Singh *et al*., 2006) and simple (Boulard *et al*., 1996) dynamic greenhouse microclimate models. Furthermore, numerous thermal models have been developed to describe heat and mass transport processes under greenhouse microclimate (Soribe and Curry, 1973; Chandra *et al*., 1989; Baille, 1989; Yang *et al*., 1990 Tiwari *et al*., 1998) and validated for various climatic conditions under different crops. Energy balance equations have been used to construct a model which permits prediction of climatic conditions in a greenhouse based on outside weather conditions (Maher and Flaherty, 1973). For describing heat and mass transport processes in a greenhouse microclimate, mathematical models have been successfully developed (Chandra *et al*., 1981; Yang *et al.,* 1990). In some of the studies, the microclimate modeling has been used to improve the accuracy of prediction under the real environment, which exhibits less uniform conditions.

Kimball (1973) simulated the greenhouse energy balance using a digital computer program. He calculated the fluxes of solar radiation from sun angle equations and the optical properties of the greenhouse walls and vegetation. The thermal radiative, sensible, latent and conductive heat fluxes were modeled. The energy balance equations were developed for various locations in the greenhouse and solved by an iterative procedure to obtain the unknown temperatures and vapour pressure. On comparing the model prediction with observed data, it was concluded that the model can accurately predict the heating and cooling requirements of a greenhouse for a wide range of greenhouse properties and environmental conditions.

Seki *et al* (1995) developed a mathematical model on greenhouse microclimate for cucumber with the combination of plant growth sub-model i.e. population dynamics and the transport process sub-model. They considered the fact that the number of plant leaves is a function not only of time and space but also of the area of an individual leaf. The proposed model gives a good prediction of plant community growth process, energy and mass transfer processes in the community. The physical factors such as spatial distribution of temperature and humidity of air, leaf temperature and PAR can be calculated from the developed transport process equations. Stanghellini and de Jong (1995) developed a model of humidity within a greenhouse in which the ambient vapour concentration results from the balance of three fluxes *viz.* crop transpiration, ventilation and condensation at the cover. With developed model, the values of the climate variables like temperature and ventilation set points can be deduced from the desired level of a crop process. It was concluded that modern greenhouse climate management, which aims at steering crop processes should incorporate a similar humidity model. Zhang *et al* (1997) presented a one-dimensional numerical model to predict the microclimate inside an unheated commercial greenhouse during a continuous period of 51 days. The main outputs of the model (hourly air and leaf temperatures and relative humidity) were used to derive the leaf wetness duration (LWLI) each day. Measured microclimate parameters inside the greenhouse were used to test the model performance during the corresponding period. Reasonable agreement was found between the predicted and measured parameters for the entire period.

Wang and Boulard (2000) simulated the microclimate of a naturally ventilated plastic house using the Gembloux Greenhouse Dynamic Model (GGDM). Improved calculations of natural ventilation flux and stomatal resistance of vegetation were introduced, based on experimental equations from previous research. A linear non-dimensional ventilation function was developed and compared with those obtained by other authors. While validating the model by comparing the predicted and observed data, a good agreement was obtained. The sensitivity analysis showed that the external wind speed and opening angle of the vents were the most important factors influencing the ventilation flux.Zhang *et al* (2002) developed a dynamic one dimensional model (PSCLIMATE) to simulate microclimate on and around leaf surface for greenhouse cucumbers. Based on energy balance of plant leaves and heat and mass transfer among air strata and leaves, the model predicts climate profiles within a plant canopy and the microclimate within a leaf surface boundary layer. The model accurately predicted air temperature and relative humidity within the plant canopy. They concluded that the model can also be used for other crop canopies or greenhouse structures once the specific characteristics of the greenhouse structure and plant canopy are defined.

Luo *et al* (2005) conducted a simulation study using the Greenhouse Process (KASPRO) model to explore alternatives to the existing Venlo-type greenhouse climate control policy under Chinese subtropical climate conditions. The results showed that using outside hourly weather data as inputs, the KASPRO model generally gives satisfactory predictions of greenhouse air temperature, humidity and canopy transpiration rate under both summer and winter climate conditions for subtropical China. Medrano *et al* (2005) evaluated and modeled the greenhouse cucumber-crop transpiration under high (up to 20 9 MJ m^{-2} d^{-1}) and low (up to 9 MJ m^{-2} d^{-1}) radiation conditions. The coefficients of the simplified Penman-Monteith formula were calibrated in order to calculate the transpiration rate of the crop to improve irrigation management in substrate cultivation. They observed that the simplified Penman-Monteith formula accounted for more than 90 percent of the measured hourly canopy transpiration rate, signifying that this formula could be used to predict water requirements of crops under Mediterranean conditions and improve irrigation control in a substrate culture. However, the model coefficients will have to be adjusted for specific climate and crop conditions.

Zhang*et al* (2005) developed a one-dimensional dynamic plant surface climate model (PSCLIMATE) for greenhouse vegetable plants (cucumber as the default plant of the model) to predict in canopy and leaf surface microclimate. The output of the model included vertical profiles of solar irradiance, air temperature, relative humidity, vapour pressure deficit and wetness at the leaf surface. The developed model predicted the canopy air temperature and relative humidity, temperature and wetness at leaf surfaces accurately. Singh *et al* (2006) developed a mathematical model (MICGREEN) consisting of a set of algebraic equations having ambient air temperature, solar radiations on normal surface, solar radiations on earth's surface, temperature of the soil under canopy and temperature of the soil at a depth of 6 cm as model inputs. The equations were solved using Gauss-Seidal Iteration method. The outputs of the model were greenhouse cover temperature, inside air temperature, canopy temperature and bare soil temperature. The results of computer model were compared with the experimental results and agreement was found between the measured and predicted values.

Yildiz and Stombaugh (2006) developed and validated a dynamic simulation model for accurate prediction of microclimate in a greenhouse as a function of dynamic environmental factors. The model has options to evaluate the effects of location, time of the year, orientation, single and double polyethylene glazings, conventional and heat pump heating and cooling systems, open and confined greenhouse systems, carbon dioxide (CO_2) enrichment, variable shading, and the use of night curtains. Conventional gas furnace and evaporative cooling, respectively, provided heating and cooling in the conventional system. Outputs of the simulation model included both temporal and vertical distribution of air, leaf, floor and cover temperatures, CO_2, relative humidity, solar radiation, and photosynthetically active radiation in addition to the dynamics of photosynthesis, respiration, transpiration, energy and CO_2 use and fixation. Comparison of experimental and predicted results showed that the microclimatological parameters were in fairly good agreement. The developed greenhouse model was useful for ecologists, plant scientists, and engineers to evaluate individual or combined effects of various forcing functions on the enclosed environment and plant responses, and to develop control strategies for different parameters.

Korner *et al* (2007) designed a simple deterministic microclimate model for dynamic greenhouse climate control. The model calculates crop temperature and latent heat of evaporation in different vertical levels of a dense canopy of potted plants. The model was validated with data attained from experiments on dynamic or non dynamic controlled greenhouse cultivation. With a more dynamic greenhouse control including assimilation lighting and screens, the prediction quality decreased but still had a 95 percent confidence interval of crop temperature prediction of 3.8°C for sunlit leaves. Simulations showed that controlling greenhouse temperature according to the predicted crop temperature rather than according to the air temperature can save energy. Energy saving is highest during winter and 12 percent energy saving was attained during January under Danish climate conditions.Hao *et al* (2008) further expanded their already developed dynamic plant surface model (PSCLIMATE-CUCUMBER) for cucumber to (PSCLIMATE-CUCUMBER) for greenhouse tomato and validated using the experimental data. Based on an energy balance of plant leaves and heat and mass transfer among air strata and leaves, the model predicts climate profiles within a plant canopy and the microclimate within a leaf surface boundary layer.Sengar and Kothari (2008) presented a mathematical model for predicting thermal environment inside the arch shape greenhouse. Predicted thermal environment inside the greenhouse helped to select the crop nursery for growing inside the greenhouse. Actual thermal environment inside the greenhouse compared with predicted thermal environment. Experimental and predicted values of greenhouse temperature were almost same with variation of 2 to 3°C.

Kavga*et al* (2009) developed a simple theoretical model that contains all the essential physics and subsequently used in parametric studies. Experimental and simulation results confirmed that, with infrared (IR) heating, inside air temperatures several degrees lower than the desired plant canopy temperature were sustained, and that this temperature difference increased proportionally to drop in outside night temperature. The model estimated energy savings in the order of 45% to 50% using the IR sources currently available, and predicted significant further benefits from improvements in the radiative efficiency of the IR sources.Baptista *et al* (2010) tested, adjusted and validated a dynamic climate model, for simulating the microclimate in unheated greenhouses under tomato crop. They selected a dynamic model which had been developed and validated (Navas *et al.*, 1998) for a greenhouse with a gerbera crop located in the Mediterranean climate conditions of the centre of Spain. The new climate model includes sub-models for ventilation and stomatal resistance appropriate for greenhouse crop system and new expressions for the convection heat transfer coefficients, which were determined by analysing experimental data. The model was validated by making comparison between predicted and measured data and a good agreement was found. This model can be used to estimate the greenhouse climate conditions based on the weather conditions and on the greenhouse-crop system characteristics. Cortes and Quijano (2010) used a temperature-humidity multizone model, which has the samecharacteristics as some biological models used in behavioralecology. In order to control each of the variables, they used a populationdynamics approach to properly allocate the resourcesin the greenhouse. A stability analysis is performed under someassumptions, and the simulations illustrated the performance ofthis method under different operational conditions.

Fitz-Rodriguez *et al* (2010) developed an interactive, dynamic greenhouse environment simulator to improve the pedagogy and understanding of the complexity and dynamic behavior of greenhouse environments. The greenhouse environment model based on energy and mass balance principles was implemented in a web-based interactive application that allowed for the selection of the greenhouse design, weather conditions and operational strategies. Several scenarios were simulated to demonstrate how a specific greenhouse design would respond environmentally for several climate conditions and to demonstrate what systems would be required to achieve the desired environmental conditions. The greenhouse environment simulator produced realistic approximations of the dynamic behavior of greenhouse environments with different design configurations for 28-h simulation periods.Xu *et al* (2010) presented a model for predicting LAI of greenhouse crops based on the quantification of easily measured morphological traits as affected by temperature and radiation. The model was evaluated by comparing leaf area index (LAI) calculated from two methods (gross degree days (GDD) and specific leaf area (SLA) based models) using independent data from other experiments. The model adequately predicted LAI based on canopy light interception as a function of node development rate along with specific leaf size and elongation rates characteristics defined on a leaf number basis. The model can be integrated with photosynthesis driven crop growth models to solve the problem caused by the difficulty in obtaining reliable SLA information, and with canopy transpiration models that need canopy LAI as input. The model can be used widely after an effective calibration procedure.

Chen *et al* (2011) developed a simple greenhouse model to describe the effect of shading nets on the inside temperatures of a greenhouse by assuming steady state thermal conditions. The detailed microclimate data of an experimental greenhouse with internal and external shading nets were collected during various weather conditions. The model was validated using experimental data collected from various conditions. The prediction accuracy of the model for air temperature was about 1.5°C. It is concluded that this model could be applied to evaluate the performance of shading nets and serve as a tool for the design of a subtropical greenhouse.Fahmy *et al* (2012) proposed a controlling technique for greenhouse indoor temperature and relative humidity. The proposed greenhouse cooling system temperature controller was designed to adjust the air volume flow rate in pad-fan cooling system to fix the greenhouse indoor temperature at 20°C and 70 percent relative humidity. They presented, a complete mathematical modeling and simulation of cooling system. Additionally, a computer model based on MATLAB SIMULINK software was used to predict the temperature and relative humidity profiles inside the greenhouse. The study realized the requirements of the greenhouse cooling system environment.Raczek and Wachowicz (2014) formulated a mathematical model of heat and mass exchange inside a big sized greenhouse. The developed mathematical model was implemented in MATLAB SIMULINK software and simulations carried out with model were used for carrying out graphical and statistical validation of a model. Analysis of simulation results allowed making statement of logical correctness of the developed model and made it possible to determine critical points of failure to adjust the model.

Wang *et al* (2014) have developed an inside temperature estimation model using the outside meteorological data and the parameters of greenhouses. The model was evaluated by the temperature monitoring data. Based on the temperature requirement of solar greenhouse cucumber and the cooling equipments, the meteorological indicators were developed for cooling in summer of solar greenhouses. The results could provide decision support and scientific basis for cooling in summer of solar greenhouses using meteorological operational service system.Fatnassi *et al* (2015) simulated solar radiation distribution, thermal air, water vapor and dynamics fields using the computational fluid dynamic (CFD) model in two different prototypes of greenhouses (Asymmetric and Venlo) equipped with photovoltaic panels on their roof. Crop cover characteristics and the interactions between crops and airflow were taken into account. Two arrangements of photovoltaic panels array were tested straight-line and checkerboard. A detailed description of the thermal, dynamic and radiation fields inside the greenhouses was obtained and the analysis of data collected during this study showed that solar radiation is more evenly distributed in the Venlo greenhouse than in the Asymmetric greenhouse. On average, the mean solar radiation transmission in the Asymmetric greenhouse was 41.6 percent whereas that of the Venlo greenhouse is 46 percent. Secondly, compared to the straight-line arrangement, the checkerboard photovoltaic panel setup improved the balance of the spatial distribution of sunlight received in the greenhouse.

Predicting the microclimate inside a greenhouse can help growers to manage crop production and designers to improve the ventilation and heating systems. The greenhouse microclimate can be investigated either by experimentation or by simulation method. Simulation methods may be performed quickly being more flexible. Microclimate parameters inside a greenhouse such as air and leaf temperatures, relative humidity and leaf wetness duration (LWD), influence the growth of the crop inside the greenhouse to a great extent. Edling *et al* (1971) presented a study for predicting cucumber leaf temperature under unstable atmospheric conditions. Zhang *et al* (1997) predicted the greenhouse microclimate inside an unheated commercial greenhouse using a one-dimensional numerical model developed by Avissar and Mahrer (1982) for a continuous period of 51 days. Luo *et al* (2005) observed that the KASPRO model can reasonably predict the greenhouse microclimate under both winter and summer sub tropical climate conditions.

Cost-benefit analysis of greenhouse cultivation: Growing crops in a greenhouse environment requires a substantial investment in capital and management resources. The two financial considerations regarding any such enterprise are profitability and cash flow. Profitability potential can be addressed through an enterprise budget, which is an itemization of costs incurred over a typical or average production cycle. The second consideration is addressed by analyzing cash flows in and out of the enterprise for a fixed interval of time, that is, through a cash flow budget.Optimal utilization of agricultural resources, particularly water and land and improving the ability of crops production during non-farming season is the main motive of greenhouse crops cultivation. The cultivation of the greenhouse crops is most intensive form of vegetable production. This method of cultivation, is supposed to allow the limited agricultural inputs to be allocated to production of strategic crops and it should be in line with optimization process. Therefore, the economic evaluation of greenhouse cultivation is of great importance.

Sengar and Kothari (2008) did a research in economic evaluation of greenhouse for cultivation of rose nursery in Rajasthan State of India. The findings of their research showed that greenhouse is an effective form of cultivation for nursery grower. Minimum survival percentage in rose nursery in greenhouse was 65% of investment made on greenhouse, the internal rate of return was 53% and thecost-benefit analysis using benefit-cost ratio was 4.5. Papadopoulos *et al.,* (2008) carried out an investment evaluation of hydroponics greenhouses, andstudied the possibility of the development of greenhouse crops cultivations, such as vegetables and flowers in Western Macedonia during 2002-2006. This comparative analysis of different hydroponics systems on the bases of the of initial investment by the net present value and the inexpensiveness of the cultivations indicated that only with subsidy is such an investment advantageous.Moustafa *et al.* (2002) in their annual report of sustainable management of natural resources and improvement of major production systems of the Arabian Peninsula stated that the benefit analysis of plastic house cultivation revealed that the total cost of these constructions can be recovered in three seasons. *Panwar et al.,* (2013) conducted a study to cost-beneût and systems analysis of passively ventilated solargreenhouses for food production in arid and semi-arid regions. In the study, economic feasibility of two veg-etable crops (i.e., cucumber and tomato) cultivated in anaturally ventilated greenhouse, and the net present worth,cost-beneût ratio, payback period, and internal rate of returnfor these crops on year-round cultivation were studied.The survival rate of cucumber andtomato was found about 95 and 96 %, respectively. The annual income from cucumber and tomato is about 6,125.86and 4,320.00 US$, respectively. The surcharge for thesecrops was 1,175.00 US$, which included labor, NPK, and$CaNO_3$. The netpresent worth for cucumber and tomato crop was found to be about 28,314.59 and 15,993.92 US$, respectively. The cost-beneût ratio of cucumber (2.17) was highercompared to that of tomato (1.77).As the cost-beneût ratio isgreater than one for these crops, hence such crops seem to beeconomically viable. As far as the payback period is concerned, it was about 5 years and 3 months for cucumber andabout 6 year and 11 months for tomato. Therefore, despite high production,tomato's payback period was higher than that of cucumber.The internal rate of return for cucumber and tomato crop isabout 35 and 20 %, respectively.

In the present scenario of perpetual demand of vegetables and shrinking land holdings drastically, greenhouse cultivation is the best alternative and drudgery-less approach for efficient utilization of land and other input resources. Greenhouse climate is the major driving force which directly affects the plant metabolic activities, fruit quality and therefore the production of greenhouse crops. Among microclimate parameters, solar radiation, temperature distribution and relative humidity are the main climatic parameters needed to evaluate the climate suitability in a region for crop growth under protected cultivation.Numerous models (static and dynamic) have been developed in the past to describe the microclimate under different greenhouse and crops conditions. The developed models have simplified the understanding of greenhouse microclimate to a great extent through accurate prediction of heating and cooling requirements of a greenhouse for a wide range of greenhouse properties and environmental conditions. Several physical factors such as spatial distribution of temperature, humidity of air, leaf temperature and photosynthetically active radiation (PAR) can be estimated using a suitable mathematical model of microclimate. Still, there exists a scope for better understanding of the relationships between microclimate and plants community by means of appropriate modeling techniques.

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