We are IntechOpen, the world's leading publisher of Open Access books Built by scientists, for scientists

5,800
Open access books available

142,000
International authors and editors

180M
Downloads

Our authors are among the

154
Countries delivered to

TOP 1%
most cited scientists

12.2%
Contributors from top 500 universities

BOOK CITATION INDEX
CLARIVATE ANALYTICS
INDEXED

WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com

Chapter

Greenhouse Crop Simulation Models and Microclimate Control Systems, A Review

Seyed Moin-E-Ddin Rezvani, Redmond R. Shamshiri, Ibrahim A. Hameed, Hamid Zare Abyane, Mohsen Godarzi, Davood Momeni and Siva K. Balasundram

Abstract

A greenhouse is a complex environment in which various biological and non-biological phenomena occur. For simulation and prediction of the climate and plant growth changes in the greenhouse are necessary to provide mathematical models. The dynamic greenhouse climate models are classified in mechanistic and black-box models (ARX). Climatic models are mainly obtained using energy balance or computational fluid dynamics. In the energy balance models, the greenhouse climatic variables are considered uniformity and homogeneity, but in the computational fluid dynamics, the heterogeneity of the greenhouse environment can be shown by 3D simulation. Crop growth simulation models are quantitative tools based on scientific principles and mathematical relationships that can evaluate the different effects of climate, soil, water, and crop management factors on crop growth and development. In this chapter, with a review of the basics of climate models in greenhouses, the results and application of some climate dynamics models based on the energy balance as well as simulations performed with computational fluid dynamics are reviewed. A review of greenhouse growth models and functional–structural plant models (FSPM) was also conducted.

Keywords: Crop, Computational Fluid Dynamics, Energy balance, Functional-structural plant, Greenhouse Climate, Growth model

1. Introduction

A greenhouse is a complex environment in which a variety of physical and biological phenomena occur that affect each other. To understand the complexities of the crop responses to its environment and management practices as well as the dynamics of the greenhouse environment in response to external conditions, greenhouse characteristics, and management, the researchers have been developing models of greenhouse environments and crops [1]. The microclimate and the plant are two subsystems in the greenhouse that exchange matter and energy. Changes in temperature, humidity, light, and concentration of carbon dioxide in the greenhouse affect the crop, and the crop also affects the microclimate by producing latent and sensible heat (transpiration) and photosynthesis. Due to the importance of

greenhouse climatic conditions and their effect on quantitative and qualitative crop yield, the use of mathematical models to study and microclimate simulation of the greenhouse is necessary. Greenhouse climate simulation models are used to describe the interactions between greenhouse plant processes (photosynthesis and transpiration) and greenhouse climate including structure shape, cover characteristics, climate control equipment, and surrounding weather conditions [2]. The enormous variety of boundary conditions and design elements makes analyzing greenhouse climate a complex task. Simulation tools are an indispensable support for greenhouse climate studies because they make it possible to take all of these characteristics into account [3]. Therefore, such a model can serve for the optimization of greenhouse design, climate control, and crop management [2]. Plant growth is a complex phenomenon that depends on soil, plant, climate, and their interactions [4]. The crop growth model is an essential part of optimizing crop management [5]. The functional-structural plant models (FSPM) community is developing models to understand the biological processes involved in plant performance and growth. Recently, due to the increasing computing power of computers, three-dimensional models of plants are used to understand the biological processes involved in crop yield and growth and to understand the interaction. The three-dimensional structure of the vegetation with the surrounding environment has been considered. The development of climate models and crop growth models with the help of the Internet of Things and cloud computing has led to attention being paid to digital twin greenhouses.

2. Mathematical models

A summary of reality is called a model. In other words, the abstract or physical representation of an object or system (from a particular point of view) is a model. Modeling helps researchers systematically analyze various scenarios in the greenhouse and predict their behavior. Models come in many forms (such as physical models, mathematical models, and statistical models) and have a variety of vital applications in all areas of science and technology. A mathematical model is a description of a system using mathematical language and its theorems and symbols. The process of creating and selecting models is called modeling. Mathematical methods and complexity in solving these models become an art that only a person who is deeply involved in it can use successfully. Modeling or mathematical modeling is the attempt to develop a mathematical model for a given system. Lumped mechanistic model, static model, steady-state model, black-box model, dynamic simulation model, mechanistic model, stochastic model, heuristic model, descriptive model, explanatory model, state variable model, and distributed fluid dynamics model are examples of mathematical modeling to solve world problems, although modeling is not limited to the above. Such a model is believed to be a simplified representation of a system to serve particular purposes. The modeling purposes are (a) knowledge integration, (b) testing hypotheses, (c) estimating the effect of conditions beyond the range of experimental data, (d) showing knowledge gaps and determine the research pathway, and (e) helping make practical decisions (input of resources, climate control in greenhouses, planning of processes) [6].

3. Climate modeling in greenhouse

The dynamic models of greenhouse climate are classified in mechanistic and black-box models (ARX) [7]. Mechanistic models describe the system it is simulating

based on knowledge of the processes that are taking place [8]. Whereas black-box models are more used for applications that involve control, optimization, and design of the greenhouse system [7]. Mechanistic models are based on physical Equations [9] and give the opportunity to be used for intelligent decision support on climate control actions [10]. They enable a quantitative approach of the greenhouse system as transparent mechanistic models, allowing for optimization algorithms to find an optimal control, and they are physically interpretable. The black box model allows statistical description based on the outputs, given inputs on a limited range [9]. Black box models do not suffer from the need to determine the value of each individual parameters. The model only uses data obtained from direct measurements and is considered an empirical approach. So, this system also provides a description of the climate of a greenhouse [9]. These models can be used to estimate the inside environment changes and they can be very helpful for climate control purposes [11]. One of the first mechanistic dynamic models of greenhouse climate was developed by Bot [12] and the first model of the greenhouse climate with optimal control purposes was proposed by Van Henten [13]. Taki et al. [14], using a multilayer perceptron neural network (MLP) model to predict greenhouse temperature, showed that the MLP model can predict the greenhouse climate with a lower Mean Absolute Percentage Error (MAPE) than a dynamic model.

The computational fluid dynamics (CFD) method is the most commonly used for simulating situations where airflow is an important component. In the greenhouse climate study, indoor environmental conditions depend on ventilation efficiency. As a result, indoor greenhouse variables such as temperature, pollution, and humidity are controlled by airflow patterns. Therefore, understanding the principles of air movement is essential to study the greenhouse environment. Computational fluid dynamics (CFD) is a powerful tool that makes it possible to predict the distribution of the climatic variables inside a greenhouse. This numerical device also makes it possible to test different scenarios without the need of experimental approach. The effect of the crop as a plant model on the climatic distribution in a greenhouse has been studied by considering the cultivation of lettuce [15] tomato [16–18]; rose [19] and begonia [20]. In these studies, the Jarvis model [21] has been used to simulate stomatal resistance, in which microclimate and transpiration rate distribution in the greenhouse has been extensively investigated in the past through CFD tools. The main disadvantage of computational fluid dynamics is the high computational costs required. These limitations limit the simulation efficiency to short periods and to identify a limited set of possible scenarios.

3.1 Componential fluid dynamic (CFD)

Computational Fluid Dynamics (CFD) is a numerical solution of the energy balance of a controlled volume that provides the ability to predict the distribution of climatic variables within the greenhouse. Over the last decade, modeling of crop interaction with the climate indoor the greenhouse has been studied. The effect of the crop on the pressure drop inside the flow causes a momentum sink. The crop is assumed as a porous medium in the Darcye Forchheimer equation to estimate the source term. It is however generally assumed that pressure forces contribute the major portion of total canopy drag and, consequently, that the viscous resistance of the crop may be neglected. The crop acts as a sink or source of heat or water vapor, which exchanges matter and energy with the surrounding environment in the form of sensible heat and latent heat flux. The sub-model of the crop was explained by Boulard and Wang [15] and then used and improved by other authors.

3.1.1 Fundamental equations

Computational fluid dynamics techniques manage the values of dependent variables as initial unknowns in a limited number of points, and then a set of algebraic equations derived from the basic equations used in the domain are solved by predefined algorithms. The three basic physical principles identified by the well-known Navier–Stokes equations are mass, momentum, and energy conservation. For an uncompressible fluid, the three-dimensional conservation equations describing the transport phenomena for steady flows in free convection are of the general form:

$$\frac{\partial(\rho\phi)}{\partial t} + \nabla.(\partial\overline{u}\phi) = \nabla.(\Gamma\nabla\phi) + S_\phi \tag{1}$$

where ρ is density (kg m^{-3}), t is time, ∇ is divergence operator, and φ represents the concentration of the dimensionless transported quantity, namely momentum, mass (air and water vapor mass fraction) and energy, and u (m s^{-1}) is the components of the velocity vector. Γ is the diffusion coefficient (m^2 s^{-1}) and S_ϕ is the source term that indicates changes in the amount of matter in the transfer. The diffusion sentence is affected by a coefficient Γ which can be the mass diffusion coefficient (D), the momentum diffusion coefficient (μ), and the energy diffusion coefficient (k). Consequently, turbulence models must be introduced in the Reynolds equations written to separate the mean flow from its fluctuating components. One of the most widely used closure procedures is the k-ε model which introduces two new phenomenological variables: the turbulent kinetic energy k, and its dissipation rate.

3.1.2 Radiative submodel

The discrete ordinate (DO) model is used to calculate the radiant heat transfer caused by the sun rays on semitransparent walls and borders. Discrete ordinate model can solve the problem,using the gray range model and assuming gray or non-gray radiation. In the discrete ordinate radiation model, the separate directions of the radiation transfer equation in the S direction are written as a field equation. The discrete ordinate (DO) equation is [22]:

$$\nabla.\left(I_\lambda\left(\vec{r},\vec{S}\right)\vec{S}\right) + (\alpha_\lambda + \sigma_s)I_\lambda\left(\vec{r},\vec{S}\right) = \alpha_\lambda n^2 I_{b\lambda} + \frac{\sigma_s}{4\pi}\int_0^{4\pi} I_\lambda\left(\vec{r},\vec{S}\right)\phi\left(\vec{S},\vec{S}\right)d\Omega' \tag{2}$$

where $\vec{r}$ is the position vector, $\vec{S}$ is the vector for radiation direction, I_λ is the radiation intensity (W m^{-2} src^{-1}) which depends on position $\left(\vec{r}\right)$ and direction $\left(\vec{s}\right)$, α_λ is the absorption coefficient (m^{-1}), σ_s is the scattering coefficient (m^{-1}), ϕ is the phase function, Ω' is the solid angle (deg), and n is the refractive index.

3.1.3 Crop sub-model

The sink of momentum due to the drag effect of the crop, is symbolized by the source term S_ϕ of the Navier–Stokes equation. This drag force may be expressed by the unit volume of the cover by the commonly used formula [23]:

$$S_\phi = \frac{\partial p}{\partial x} = -\rho L C_D u^2 \tag{3}$$

where u is the air speed, L the leaf area density ($m^2\,m^{-3}$) and C_D a drag coefficient. For a mature greenhouse tomato crop C_D is 0.32.

3.2 Review of CFD studies in greenhouse

Kacira et al. [24] investigated the effect of wind speed, side vents, and the number of spans on natural ventilation of a multi-spans greenhouse by numerical simulation in a CFD software. The results showed that the maximum amount of greenhouse ventilation was achieved by the simultaneous use of side and roof vents. The ratio of ventilation to the ground area of the greenhouse was 9.6%, which was lower than the recommended ratio of 15 to 25%. The results showed a significant decrease in the amount of ventilation with increasing the number of openings. Baeza et al. [25] considered the cooling of a greenhouse with natural ventilation to be conditional on the creation of a suitable and sufficient combination of air exchange from the roof and side vents to remove the excess heat of the sensible heat by moving the air through the vegetation. The CFD simulation results showed the most of the exchanged air was at the top of the canopy and warm harmful areas were created inside the canopy due to the slow movement of air. Flores-Velázquez [26] in a study using CFD showed that the wind pattern inside the greenhouse was greatly influenced by the wind speed outside the greenhouse and the number of greenhouse spans. In the case of greenhouses with 3 or 4 spans, ventilation was independent of the roof vents, but in greenhouses with five or more spans, side ventilation prevailed over roof ventilation. Flores-Velazquez et al. [27] in a study investigated the temperature exchange and distribution in a greenhouse with natural and mechanical ventilation systems with 30 and 100% openness of roof vents in four greenhouse lengths of 28, 50, 75, and 100 m. The results showed a strong linear relationship between temperature slope and greenhouse length. Simultaneous use of roof ventilation and fan compared to mechanical ventilation alone improved the air exchange rate (22%) and the uniformity of the greenhouse climate. With increasing the length of greenhouses, the advantage of natural ventilation over mechanical ventilation was greater. Increasing the capacity of the fans generally reduced the temperature, but the effect was less severe in openness greenhouse roof vents. Roy et al. [28] simulated the temperature and humidity distribution in a semi-enclosed 960 m^2 glasshouse with a tomato crop using CFD. Radiation exchange simulation was modeled with a separate directional radiation model (DO) and tangible, latent and radiant heat transfer along with product activity (aperture resistance) and water vapor transfer in vegetation with a porous and semi-transparent medium. To limit the computation time and the size of the grid, the geometric domain was limited to the greenhouse walls. The simulation values and experimental data were generally in good agreement, however, a disagreement between the two was evident for the concentration of water vapor during the opening period of the valves. These differences indicated the impossibility of obtaining accurate simulation values with a limited amplitude when the skylights are open. Simulation of temperature and water vapor concentration patterns inside the greenhouse showed that doubling the airflow rate leads to a significant change in the climate distribution inside the greenhouse. Higher values of airflow rate do not further change these parameters. Flores-Velázquez et al. [29] used CFD modeling in tomato-growing greenhouses in a study aimed at proposing alternatives to environment management, estimating energy costs, and the economic costs of using fans. Results showed that in areas with mild summers, the use of mechanical and natural ventilation together is a suitable alternative to reduce temperature and energy costs. The use of combined ventilation due to high temperature in the hours of maximum radiation, while reducing problems, does not affect production costs.

Molina-Aiz et al. [30] investigated the effects of four different greenhouse vents arrangements and two outside wind speeds on ventilation and temperature distribution in uncultivated greenhouses in the Almera region of Spain. The results showed that the ventilation vents arrangement was affected by airflow, ventilation intensity, and air temperature distribution in the greenhouse. For different settings, the wind direction perpendicular to the openings and outside wind speed 5 m s^{-1}, calculated airflow from 70.1 to 134.9 m^3 s^{-1} and for wind speed 1 m s^{-1} from 21.0 to 43.3 m^3 s^{-1} were variable. Bournet et al. [31] studied the combination of the side and roof vents with consideration of ventilation, airflow patterns, and temperature distribution in a four-span greenhouse (2600 m^2) equipped with continuous roof vents and benches supporting ornamental crops. The results showed that the arrangement with side and roof vents led to a maximum flow rate of 12.3 times air exchange per hour with a wind speed of 0.15 m s^{-1}.

Fatnassi et al. [19] investigated the effect of insect screens on airflow and climatic conditions of multi-span 1000 m^2 square greenhouses by CFD. The main results showed that the increase in temperature and humidity due to the use of insect screens can be corrected by the simple arrangement of the system, such as the intelligent selection of roof vents and the use of additional side vents. Bartzanas et al. [32] simulated the effect of insect screens in a tunnel greenhouse with a tomato crop and showed that reducing the porosity of the insect screens led to a gradual increase in temperature and humidity and a decrease in air velocity. Majdobi et al. [33] in another simulation in the same greenhouse showed that insect screens reduce the ventilation rate by 46%.

Chen et al. [34] adapted the CFD model to simulate the distribution of velocity and air temperature in greenhouses with fan and pad cooling systems in summer. The CFD simulations showed that when the crop canopy height is between 2 to 3 m, the fan and pad height options from the ground level of 0.6 and 1.4 m, respectively, and the fan and pad height of both 1.4 m were appropriate.

Fidaros et al. [35] investigated the simultaneous effect of solar radiation distribution and, ventilation in a tunnel tomato greenhouse at different summer days hours. Simulations showed the effect of the angle of incidence of the incoming radiation radius on the distribution of solar radiation inside the greenhouse. Another result was the predominance of forced convection due to mechanical ventilation. Baxevanou et al. [36] simulated the effect of solar radiation distribution in a tunnel greenhouse in two dimensions with discrete ordinate (DO) model according to the thickness, optical and thermal properties of the cover. The results showed that the greenhouse cover with high absorption of solar radiation disrupts natural ventilation, increases the air temperature inside the greenhouse due to the phenomenon of convection and the development of secondary recirculation. At the same time, high absorption reduces photosynthetically active radiation (PAR). Ortiz-Vazquez et al. [37] reported that the main problem of large commercial greenhouses is inadequate ventilation and increased production costs due to the use of air conditioning. They studied the environmental conditions of a large commercial greenhouse to optimize the design using CFD and showed that the large geometry of the greenhouse and the height of the greenhouse cover determine the impact of incoming radiation inside the greenhouse and thus the environmental conditions.

Ali et al. [23] a special sub-model to simulate the distribution of transpiration and climate around potted plants in water-restricted greenhouses in the form of a 2D transient CFD model with user-defined functions to match product interaction by developed the climate inside the greenhouse. The crop was considered as a porous medium, and special source terms for transpiration and sensible heat transfers were added. The simulation results showed the model's ability to accurately predict transpiration, air temperature, leaf, and indoor air humidity in irrigation

regimes. Experiments showed that water supply can be reduced without a significant effect on transpiration rate and thus plant growth potential up to 20%. Piscia et al. [3] proposed a CFD model for climatic simulation and night condensation in a plastic-covered four-span greenhouse. The results, while displaying the importance of radiation heat loss losses, showed that the greenhouse roof is the coolest surface for condensation of water vapor produced by the crop.

Boulard et al. [38] developed a CFD model for predicting the distribution of temperature, water vapor, and carbon dioxide in a semi-enclosed glass greenhouse equipped with an air conditioning system. Sensible and latent heat fluxes in the crop rows were added to the main model through the radiation model of discrete ordinate (DO) and changes in carbon dioxide concentration through the photosynthesis model. The simulated values of temperature, humidity and carbon dioxide concentration had a good agreement with the measured values. The simulation results for investigating the vertical distribution of temperature and humidity for two leaf area density of 2.95 m^{-1} and 5.9 m^{-1} showed that long and dense vegetation intensifies the cooling of indoor air as well as increases temperature layering.

Rezvani [39] investigated mechanical ventilation and pad-fan to improve the climatic conditions in an asymmetry commercial greenhouse with an area of 4333 m^2 in June. Ansys Fluent 16 software was used to prepare the computational fluid dynamics model, and to calculate the rate of penetration and absorption of radiation by vegetation, vapor pressure deficit, leaf temperature, and transpiration was coded using the user-defined function (UDF). The results showed that natural ventilation could not improve the climatic conditions inside the greenhouse and the use of climate control equipment is necessary. Mechanical ventilation also causes more uniformity and homogeneity of the greenhouse climate, but depending on the climatic conditions around the greenhouse may not be able to improve the greenhouse climate. The computational fluid dynamics model simulated the real conditions properly and showed that the addition of a pad-fan in the greenhouse in June could reduce the temperature from 38.0 to 22.7, increase the relative humidity from
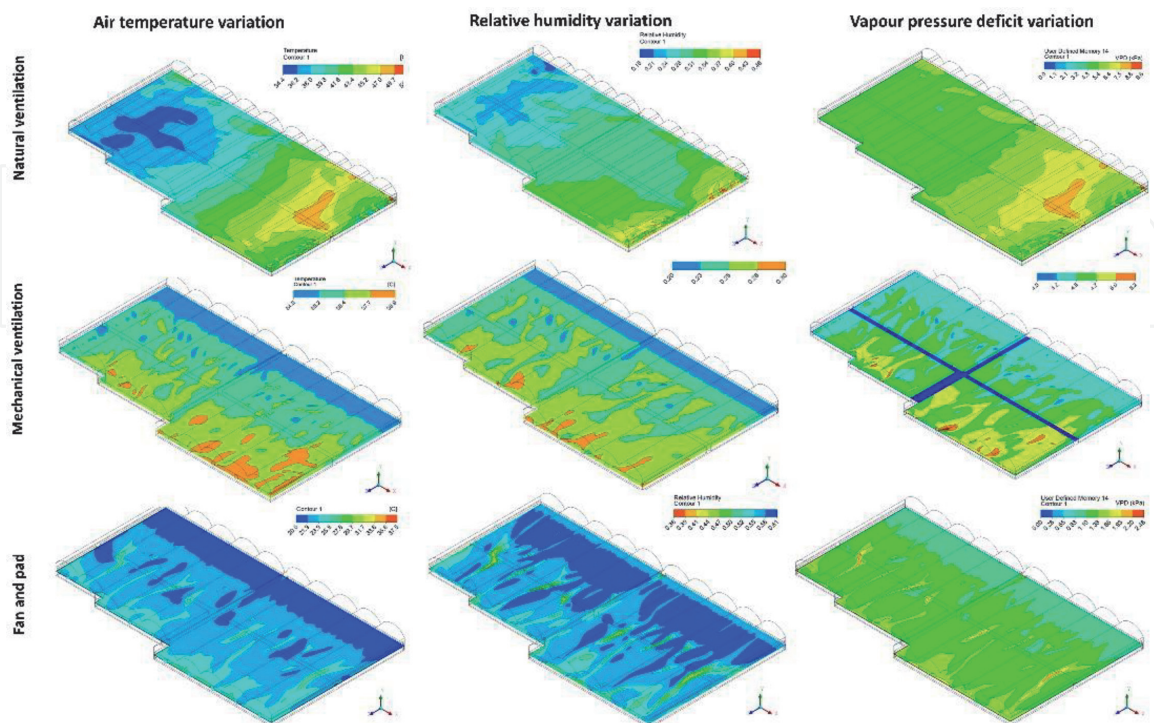

Figure 1.
Simulation of temperature, relative humidity and vapor pressure deficit in natural ventilation, mechanical ventilation, and cooling system (fan and pad) in a commercial greenhouse. Simulation time is 14:00 on 10 June 2018.

29.5% to 55.5% and reduction of vapor pressure deficit from 4.51 to 1.26 kPa and optimize the environmental conditions for the product (**Figure 1**). The results showed that in large commercial greenhouses, it is better to prevent non-uniformity due to structural asymmetry by constructing a greenhouse structure symmetrically.

4. Energy and mass balance

In the energy balance model, the greenhouse is considered as a "perfectly stirred tank" assuming the uniformity and homogeneity of the greenhouse variables such as temperature and humidity [40]. This assumption causes the energy balance model computationally is done fast and explicit, but on the other hand, it is a source for certain limitations. Calculations in the energy balance model require some priori and empirical information of different coefficients such as ventilation intensity and heat transfer coefficient. Energy balance simulation is based on the analysis of heat and mass balance equations used throughout the greenhouse system [41].

Energy and mass balance equations are used to estimate temperature, absolute humidity and CO_2 in a greenhouse [42, 43]:

$$\frac{dT}{dt} = \frac{1}{C_{cap}} \left(Q_{sun} - Q_{cov} - Q_{trans} + Q_{lamp} - Q_{vent} + Q_{he,heat} - Q_{he,cool} + Q_{pipe} \right) (°C\ s^{-1})$$

(4)

$$\frac{d\chi_{air}}{dt} = \frac{1}{h} \left(\phi_{trans} - \phi_{cov} - \phi_{he,cool} - \phi_{vent} \right) (g\ m^{-3} s^{-1})$$

(5)

$$\frac{dCO_{2,air}}{dt} = \frac{1}{h} \left(\phi_{c.inj} - \phi_{c,ass} - \phi_{c,vent} \right) (g\ m^{-3} s^{-1})$$

(6)

where h is the average height of the greenhouse, incoming radiation Q_{sun}, heat losses through the cover Q_{cov}, transpiration by the crop Q_{trans}, artificial lighting Q_{lamp}, natural ventilation Q_{vent}, heating $Q_{he,heat}$ and cooling $Q_{he,cool}$ with the heat exchangers, and heating by the pipe rail system Q_{pipe} (W m^{-2}). The vapour balance is influenced by crop transpiration ϕ_{trans}, condensation on the cover ϕ_{cov}, condensation in the heat exchangers due to cooling $\phi_{he,cool}$, and vapour exchange with outdoor air by natural ventilation ϕ_{vent} (g m^{-2} s^{-1}) (**Figure 2**). $\phi_{c,inj}$ is the injection of pure industrial CO_2 to the greenhouse, $\phi_{c,ass}$ is the assimilation of CO_2 by the crop, and $\phi_{c,vent}$ is the CO_2 exchange with outside.

4.1 Review of dynamic climate models studies in greenhouse

Kindelan [44] used a dynamic model to simulate the indoor environmental conditions of the greenhouse. The external climatic variables used in the initial simulation were: constant wind speed, constant relative humidity, solar radiation, and air temperature. In order to simulate the internal environment by the energy balance method, the system is divided into four elements; soil, plant, internal air and cover, modelling the heat and mass fluxes between these elements. The dynamic model was used to predict temperature, humidity, heat flow inside the greenhouse using ventilation conditions, night heating, and vegetation percentage.

A dynamic mechanical model of the greenhouse climate developed by Bot [12] includes four temperature variables: greenhouse cover, air, crop canopy, and four layers of soil, as well as air and soil moisture. The physical processes in energy balance were transient, convection, conduction, ventilation, and radiation. Mass balance, on the other hand, is considered convection, ventilation, transpiration, and
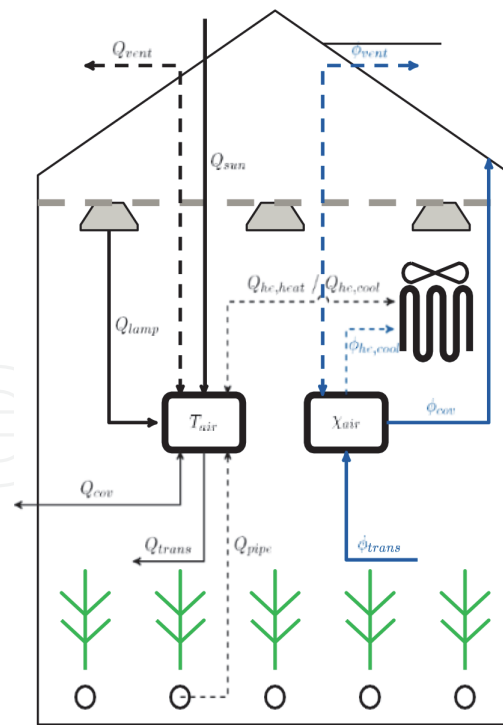
Figure 2.
Display Tair and χair climatic variables, and related energy fluxes Q and vapor fluxes φ (source: [42]).

condensation. The input variables were temperature, humidity, sunlight, and wind speed outside the greenhouse. In a more detailed model, the concentration of carbon dioxide in the air was considered as another variable [45] in the greenhouse. Therefore, the physical and biological processes in the more accurate model were CO_2 injection, product photosynthesis, and product respiration rate. In the latter model, the temperature of the heating pipes was also in the energy balance.

The greenhouse process (KASPRO) model is constructed from modules describing the physics of mass and energy transport in the greenhouse enclosure, and a large number of modules that simulate the customary greenhouse climate controllers [46]. The state variables included air temperature, carbon dioxide concentration and humidity (water vapor or partial vapor pressure). In the case of the temperature, unsteady-state balances were carried out at the greenhouse cover, the air above a thermal screen, air below a thermal screen, on the crop canopy, in the floor and in six soil layers. For carbon dioxide and air humidity, mass balances were performed above and below a thermal screen. The standard heat exchange theory is used for the convective heat exchange between all the surfaces calculated. The KASPRO climate model can also be used to control heating, ventilation, dehumidification, humidification, shading, artificial light and carbon dioxide supply. The model can also be used to characterize the performance of the boiler, short-term and seasonal heat storage facilities, simultaneous production of heat and electricity and heat pumps. The input variables were temperature of the sky, temperature outside the greenhouse, temperature of a deep soil layer, temperature of upper and lower heating pipe, external vapor pressure, carbon dioxide concentration and wind speed outside the greenhouse. Control variables were CO_2 supply, window aperture, thermal screens and artificial lighting. The physical processes involved in the mass and heat unsteady-state balances included radiative heat exchange, convective exchange, ventilation, condensation, transpiration and conduction. This model was developed for glasshouses [46].

Vanthoor [47] developed a model to study the effects of outdoor climate and greenhouse design on the indoor greenhouse climate. To use the greenhouse design

method, which focused on optimizing a set of design elements, this model had to meet the following three: 1) Predicting the temperature, vapor pressure, and CO_2 concentration greenhouse indoor air, for different greenhouse designs and climatic conditions, 2) Ability to consider greenhouse construction parameters and climate conditioning equipment, 3) Possibility to make it combine it with tomato yield model. The dynamic model was approved for four different greenhouse designs under three climatic conditions: a temperate marine climate, a Mediterranean climate and a semi-arid climate.

Mobtaker et al. [48] investigated six greenhouse forms with north–south and east–west orientations in terms of energy consumption in the climate of Tabriz, Iran. The minimal extra thermal energy required to maintain suitable temperature conditions for plant growth was observed in a single-span greenhouse in an east–west direction with a north brick wall. The results showed that the northern brick wall could reduce greenhouse heating demand by 31.7%.

Using a single-span semi-solar greenhouse for experimental research designed and built by Mohammadi et al. [11], Mobtakar et al. [48] developed a dynamic model for predicting indoor air temperature in the greenhouse. The results showed that the predicted and measured data are consistent.

Taki et al. [14] investigated a dynamic climate model in a semi-solar greenhouse was designed and constructed at the North-West of Iran in Azerbaijan Province. Crop, soil, cover and thermal screen temperature, and air temperature below and above the screen were measurement. Then the temperature in different parts of the greenhouse was estimated by a dynamic heat and mass transfer model with initial values and considering the evapotranspiration of the crop. It was reported that the predicted and experimental data were in good agreement. Yildiz and Stombaugh [49] developed a dynamic simulation model for predicting climate in the greenhouse as a function of dynamic environmental factors. The model can consider the effects of location, time of the year, orientation, single and double polyethylene glazing, conventional and heat pump heating and cooling systems, open and confined greenhouse systems, CO_2 enrichment, variable shading, and the use of night curtains. The greenhouse heating and cooling systems were a conventional gas furnace and evaporative cooling, respectively. The model was able to simulate the temporal and vertical distribution temperatures of air, leaf, floor, and cover. Also, the model simulated relative humidity, CO_2, photosynthetic active radiation, respiration, transpiration, energy, and CO_2 utilization. Comparison of measured and predicted results showed that the simulated and predicted parameters are in good agreement.

Salazar-Moreno et al. [50] used a dynamic energy balance model to predict the temperature in a 120 m^2 greenhouse with polyethylene cover, natural ventilation, and tomato cultivation in central Mexico. The model considered plant transpiration, ventilation, condensation inside the greenhouse, outdoor climatic conditions, crop characteristics (leaf area index, stomatal and aerodynamic resistance), cover properties and greenhouse characteristics. The results showed that the mean absolute error (MAE), root mean square error (RMSE), and model efficiency (EF) were 1.86°C, 2.256, and 0.657, respectively. After calibrating, the model efficiency increased to 33.84% and received 0.89. Although the predicted transpiration was not close to the values in the sources, the model was effective as a tool to analyze the temperature behavior in the greenhouse.

Joudi and Farhan [51] developed a dynamic model that considered the exchange of soil surface heat with greenhouse air to more accurately predict indoor temperatures. The input parameters of the model were meteorological conditions and thermal properties of the indoor air, cover, and soil of the greenhouse. The results showed that the simulated and experimental data were in good agreement.

5. Crop growth model

Crop growth model is an essential part of the optimization for cultivation management [5]. Crop growth simulation models are quantitative tools based on scientific principles and mathematical relationships that can evaluate the different effects of climate, soil, water, and crop management factors on crop growth and development. Based on the advances made, today the approach of using computer software to manage agricultural production systems is considered a powerful tool. Crop production management (irrigation, fertilization, pest and disease control), climate change, climate fluctuations, yield forecast, environmental pollution, sustainable agriculture, and many other aspects are studied with the above approach.

The first crop growth models were built for open field crops, and greenhouse crops models were developed decades later. There is little difference between farm and greenhouse crop growth models [52].

The main reforms that were needed included the following: modified of radiation conditions due to greenhouse cover, use of complementary lighting and screens (and rapid changes in radiation), extreme climatic conditions in winter and summer, a more detailed description of the effects of temperature on crop performance, effect of CO_2 concentration, and the crucial role of maintenance respiration in winter cultivation [52]. Process-based models are mostly used for crop model development. In process-based models, the rates of growth and development are derived from basic principles in heat and mass transfer and plant physiology. Common processes for plants are photosynthesis, respiration, growth and development. According to the model application, the stages of plant flowering and fruiting may be added to it [53].

Growth models consist of two categories: descriptive and explanatory models. A descriptive model, based on existing theoretical knowledge and practical experience, determines the relation between the research factors using regression analysis of mass crop data. The explanatory model describes the relationship between environmental factors, crop management and crop growth, morphological growth and yield formation process based on the principle of dynamics [5].

5.1 Crop growth models in greenhouse

There is a wide range of explanatory models for greenhouse crops, with several more prominent models including TOMGRO and HORTISIM for general crops [53–55]. Some of the well-known simulation models for tomato plants [56] include TOMSIM and SUSROS87 [57], TOMPOUSSE [58], TOMGRO [1, 59]. There is seen to be a common weakness with these models in that their parameters are specific for the climate condition and greenhouse design they were derived from. In addition, the complexity of the interactions between the greenhouse elements and the crop itself, makes it often impossible to correctly predict microclimate effects on the final yield with the same model parameters. In Jones et al. [1] study, it was claimed that the simplified TOMGRO model is possible to use for different climate conditions with the same parameters derived from their experiment. The first version of TOMGRO [59] and the third version, respectively had 69 and 574 state variables for the simulation of tomato growth on the basis of three inputs measured inside the greenhouse environment: the photosynthetically active radiation in [μmol m^2 s^{-1}], air temperature [°C] and CO_2 concentration CA [ppm]. A simplified version of TOMGRO [1] was developed with the objective of providing a practical application which only had five steady-state variables: (i) node number for the main stem, (ii) leaf Area Index, (iii) total plant dry weight (WT), (iv) total fruit dry weight (WF),

and (v) mature fruit dry weight (WM). Some of the studies related to the evaluation and adaptation of TOMGRO model to specific climate conditions and cultural practices, a few can be found in [5, 60, 61]. It should be noted that the simplified TOMGRO model only takes into account the effect of air temperature and light condition, while other important variables such as CO_2 concentration were not included in this version.

A model-based method to design greenhouses for a broad range of climatic and economic conditions, a tomato yield model developed by Vanthoor et al. [62] describes the effects of greenhouse climate on yield. The tomato yield was simulated for various light conditions and concentrations of CO_2 for optimal and non-optimal temperatures in the Netherlands and southern Spain. The model simulated the effects of extremely low as well as average high temperatures on the yield and harvest time of the first fruit with acceptable accuracy [62]. Lin et al. [5] stating that today the models for predicting the performance of the greenhouse crop have their specific application conditions, which may not ensure the accuracy of the results if the greenhouse environment changes. To solve this problem, they studied two widely used tomato growth models TOMGRO and Vanthoor, and then proposed an integrated model. Results showed compared with TOMGRO and Vanthoor models, the output of the integrated model was more reasonable and universal, and the model output was closer to the actual value.

5.2 Functional–structural plant (FSP) modeling

The need to integrate expanding knowledge into the plant sciences has led to the development of advanced modeling approaches, such as functional-structural plant (FSP) modeling which is the result of cross-fertilization between the domains of plant science, computer science, and mathematics [63]. These models provide an opportunity for computational botany to address issues in complex plant systems that cannot be fully explained by experimental approaches alone. FSP modeling is now a well-established approach that has been perfected over the years. FSP models simulate growth and morphology of individual plants and their interaction with the environment, from which the complex properties of the plant community emerge [64]. Investigated the distribution of light interception in a canopy, optimal pruning strategies in orchards, and grass branching about plant population density leading to take into account plant architecture and its development as an integral component [64]. Functional–structural plant (FSP) models have been used widely for over two decades to understand the complex interactions between plant architecture and underlying processes driving plant growth [65]. Functional–structural plant models (FSPMs) were initiated after the concepts of plant architecture became widely acknowledged in botany and in parallel with development of the computational power offered by personal computers [65]. FSP modeling makes it possible to simulate the three-dimensional structure of each plant individually over time. The three-dimensional structure can consider the retention and scattering of light on the leaf surface as a function of leaf size, angle and optical properties. The obtained information can be used to characterize photosynthesis, photomorphogenesis, and overall plant growth and development. Therefore, by considering phenotypic variability between individuals and plastic responses to environmental conditions, as well as by changing plant architecture such as pruning or herbivore, FSP modeling can be used to understand the behavior of a single plant to the performance of the entire canopy [64]. Conceptual diagram of functional-structural plant modeling, which can be formed for scaling from gene to community integration level (**Figure 3**). FSP models typically simulate the three-dimensional structure of plants as a result of individual plant growth, driven by plant physiological processes,
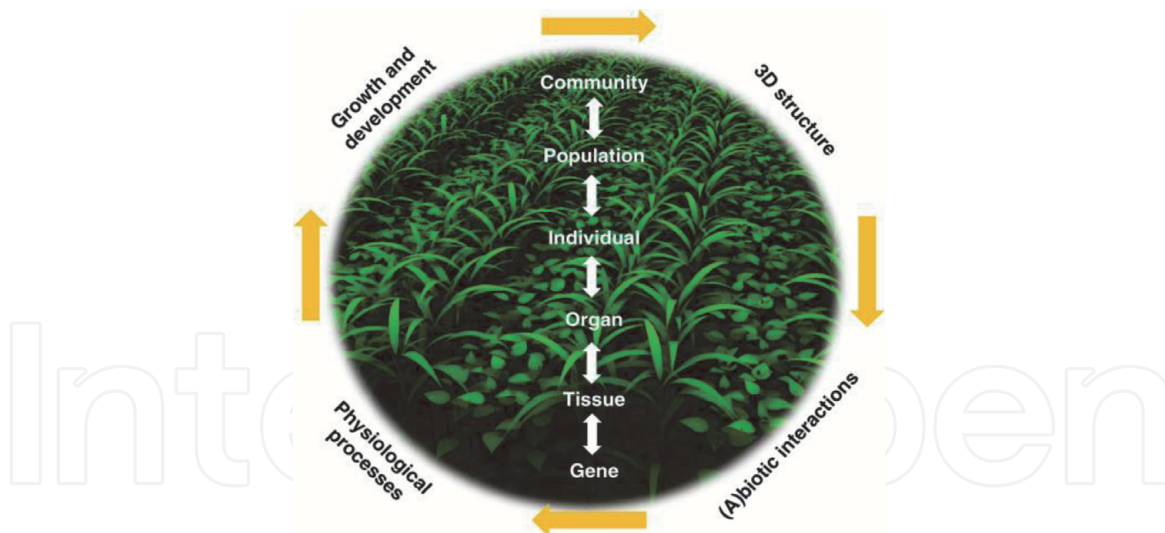
Figure 3.
Conceptual diagram of functional–structural plant (FSP) modeling (source: [63]).

which in turn are influenced by biological and non-biological factors of vegetation (Light, temperature, fungi, insects, etc.). In turn, the distribution of these factors in the canopy is determined by the three-dimensional structure of the plants.

6. Greenhouse climate and crop models combination

Vanthoor [47, 62, 66, 67] developed a greenhouse environment system model that includes a greenhouse microclimate model, a greenhouse growth model, and an economic model.

An FSP combined with a climate model helps to study the distribution of climatic parameters in vegetation and the interaction of crop and environment. It also shows the effect of climatic conditions such as temperature, humidity, carbon dioxide concentration, and light conditions on photosynthesis, dry matter accumulation, crop yield, and distribution of fungal diseases in plant populations [68–72].

Szanto [73] determined the optimal row orientation of greenhouse tomato with special emphasis on stomatal conductance, its dynamics, thus assimilation and transpiration, using functional-structural plant modeling. A coupled steady-state photosynthesis and stomatal conductance model was used to evaluate the effects of row orientations on crop performance. Functional-structural plant model of greenhouse tomato was established in GroIMP 1.5, using ray tracing for light environment simulations. Results showed that stomatal dynamics may be a significant reduction factor of assimilation. The vertical distribution of photosynthesis and transpiration did not show discrepancies between the row orientations. The diurnal pattern of assimilation demonstrated that at low solar elevation angles, the direct irradiance should reach the canopy in parallel with the rows, while at higher solar elevation angles, row orientation has a weak effect on the light interception.

Buck-Sorlin et al. [74] used structural plant modeling (FSPM) including a virtual greenhouse environment with the crop, light sources (diffuse and direct sunlight and lamps) and photosynthetically active radiation (PAR) sensors to better understand the processes that help produce the quality and quantity of roses. The crop model is designed as a multiscale FSPM with plant organs (axillary buds, leaves, internodes, flowers) as basic units, and local light interception and photosynthesis within each leaf. The model was able to reproduce PAR measurements at different canopy positions, times of the day, and light conditions. For different typical

cultivation scenarios, the simulated incident and the adsorbed PAR, and the net uptake rate in upright and bent shoots showed characteristic spatial and daily dynamics.

Wiechers et al. [75] investigated the effect of the distribution of environmental factors and canopy architecture on growth imbalances between individual fruits of cucumber (*Cucumis sativus*) in a greenhouse. They used the formalism of the L-system to create FSPM, which combined a plant three-dimensional structure model, a photosynthetic biochemical model, and an adsorption model involving fruit growth based on potential growth rate (RP), abortion and dominance. Simulations were performed for a dense row with sparse symmetrical canopies. The results showed that simple partitioning models unsuccessful in simulating the growth of individual fruits. The model had good results in determining the abortion and dominance threshold. There was good agreement in simulating the duration of fruit growth, abortion rate with measurements and reproduction of conditions in which the fruit could be harvested earlier.

Zhang [70] conducted experiments in greenhouses with cut-flower plants (lilies and roses) to determine the response of plants (including response to leaf photosynthetic traits and plant architectural traits) to changes in PAR, R: FR, water level and nitrogen, and study the presence of bent shoots. Then, modeling studies were performed to quantify the photosynthetic response to these conditions at the leaf, plant and crop levels. The results showed that to quantify the effects of environmental factors, plant responses, and biotic processes on crop yield, the combination of the FSP model with detailed leaf photosynthesis models (for both steady-state and dynamic photosynthesis) and phylloclimate models can be used.

Zhang et al. [72] introducing a new method for evaluating micro-light climate and thermal performance in a Liaoshen-type Solar Greenhouse (LSG) incorporated 3D architecture tomato canopy, simulated using an FSP model. The exact surface temperature of each component of the greenhouse and tomato crop was simulated using advanced light modeling techniques. Considering the simulated light absorption as input, the thermal conditions were obtained using particular energy balance equations. Results showed that simulated greenhouse temperatures from cover, ceiling, indoor, wall, canopy and soil had a good agreement with the experimental data.

7. Future trends

Evers et al. [76] are conducting a study on a digital twin greenhouse that aims to develop a simulation model that predicts tomato plant growth in 3D (**Figure 4**). The model simulates crop yield, CO_2 uptake, and use of nutrients, energy, and water, as well as profit and environmental impact. Simulations are based on real-time measurements of tomato plants and their growing conditions. The core of the study is based on the concepts of functional-structural plant (FSP) modeling. The environmental variables driving plant growth and development will be simulated by a greenhouse module based on the Kaspro model. Data from several sensors such as the multi-spectral 3D laser scanner, chlorophyll fluorescence camera, thermal camera, and climate sensors, will be processed to estimate plant traits and climate conditions. The focus is therefore on estimating plant traits from raw sensor data. Based on the model predictions, crop management strategy can be adjusted, and improved plant traits can be identified. The future trend in greenhouse crop production [77] is toward the use of digital technology and robotics [78], artificial intelligence, and collecting greenhouse climate data using IoT sensors [79] in
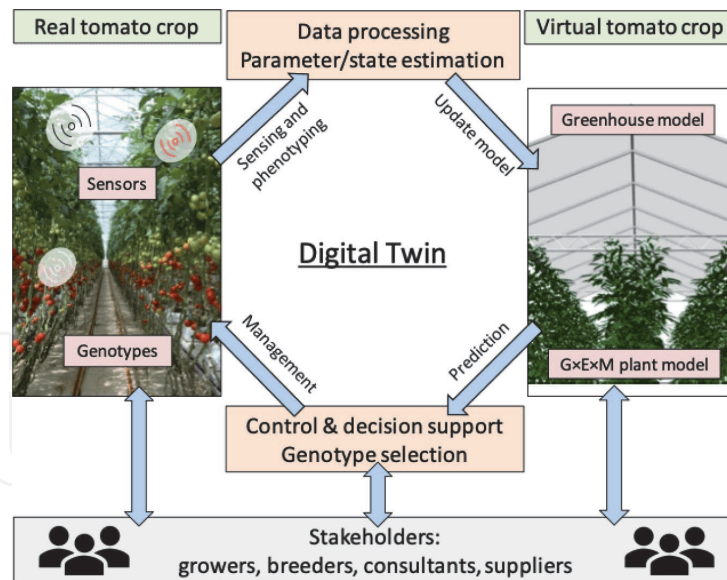
Figure 4.
Concept map of the Virtual Tomato Crops digital twin. (G × E × M = interaction between genotype, environment and management) [76].

combination with FSP growth models and analyzing them in the cloud for preparing a digital version of a real greenhouse.

8. Conclusion

To understand the complexities of the crop responses to its environment and management practices as well as the dynamics of the greenhouse environment in response to external conditions, greenhouse characteristics, and management, the researchers have been developing models of greenhouse environments and crops. The most prominent models of climate dynamics based on energy balance are KASPRO and Vanthoor models. The greenhouse process (KASPRO) model is constructed from modules describing the physics of mass and energy transport in the greenhouse enclosure and the large number of modules that simulate the customary greenhouse climate controllers. The climate controller of KASPRO enables climate management using heating, ventilation, dehumidification, moistening, shading, artificial illumination, and carbon dioxide supply. Vanthoor [47] developed a model to study the effects of outdoor climate and greenhouse design on the indoor greenhouse climate. Extensive studies by computational fluid dynamics have been performed on the effect of ventilation vents arrangement, climate control equipment, greenhouse dimensions, solar radiation, and crop canopy on airflow and indoor climate of the greenhouse. The crop growth model is an essential part of the optimization of cultivation management. Plant dynamics models are often designed for specific conditions and their application in different conditions reduces the accuracy of their results. TOMGRO and Vanthoor are two widely used tomato growth models. With the development of computers, FSP models simulate growth and morphology of individual plants and their interaction with the environment, . from which the complex properties of the plant community emerge. Functional – structural plant models (FSPM) have been used to simulate tomatoes, cucumbers, and roses in the greenhouse. The digital twin greenhouse is currently being studied and developed using IoT sensors, climate models (KASPRO), and FSP models.

Author details

Seyed Moin-E-Ddin Rezvani[1], Redmond R. Shamshiri[2]*, Ibrahim A. Hameed[3], Hamid Zare Abyane[4], Mohsen Godarzi[5], Davood Momeni[6] and Siva K. Balasundram[7]

1 Agricultural Engineering Research Department, Hamedan Agricultural and Natural Resources Research and Education Center, AREEO, Hamedan, Iran

2 Leibniz Institute for Agricultural Engineering and Bioeconomy, Potsdam-Bornim, Germany

3 Department of ICT and Natural Sciences, Faculty of Information Technology and Electrical Engineering, NTNU, Ålesund, Norway

4 Department of Irrigation and Drainage, Faculty of Agriculture, Bu-Ali Sina University, Hamadan, Iran

5 Department of Mechanical Engineering, Faculty of Engineering, Bu-Ali Sina University, Hamadan, Iran

6 Agricultural Engineering Research Department, Isfahan Agricultural and Natural Resources Research and Education Center, AREEO, Isfahan, Iran

7 Department of Agriculture Technology, Faculty of Agriculture, Universiti Putra Malaysia, Serdang, Selangor, Malaysia

*Address all correspondence to: rshamshiri@atb-potsdam.de

IntechOpen

References

[1] Jones, J.; Kenig, A.; Vallejos, C. Reduced state–variable tomato growth model. Transactions of the ASAE. 1999; 42: 255 p.

[2] Luo, W.; de Zwart, H.F.; DaiI, J.; Wang, X.; Stanghellini, C.; Bu, C. Simulation of greenhouse management in the subtropics, Part I: Model validation and scenario study for the winter season. Biosystems engineering. 2005; 90: 307-318 p.

[3] Piscia, D. Analysis of night-time climate in plastic-covered grenhouses. 2012: p.

[4] Singh, A.K. Crop growth simulation models. IASRI, New Delhi. 1994: 497-509 p.

[5] Lin, D.; Wei, R.; Xu, L. An Integrated Yield Prediction Model for Greenhouse Tomato. Agronomy. 2019; 9: 873 p.

[6] Vos, J.; Marcelis, L.; Evers, J. Functional-structural plant modelling in crop production: adding a dimension. Frontis. 2007: 1-12 p.

[7] López-Cruz, I.; Fitz-Rodríguez, E.; Salazar-Moreno, R.; Rojano-Aguilar, A.; Kacira, M. Development and analysis of dynamical mathematical models of greenhouse climate: A review. European Journal of Horticultural Science. 2018; 83: 269-279 p.

[8] Watt, J. 3D Crop Modelling [thesis]. London: University College London; 2013.

[9] Flores-Velázquez, J.; Rojano, A.; Rojas-Rishor, A.; Bustamante, W.O. Computational Fluid Dynamics Achievements Applied to Optimal Crop Production in a Greenhouse. New Perspectives in Fluid Dynamics. 2015: 77 p.

[10] Hemming, S.; de Zwart, F.; Elings, A.; Petropoulou, A.; Righini, I. Cherry Tomato Production in Intelligent Greenhouses—Sensors and AI for Control of Climate, Irrigation, Crop Yield, and Quality. Sensors. 2020; 20: 6430 p.

[11] Mohammadi, B.; Ranjbar, S.F.; Ajabshirchi, Y. Application of dynamic model to predict some inside environment variables in a semi-solar greenhouse. Information processing in agriculture. 2018; 5: 279-288 p.

[12] Bot, G.P. Greenhouse climate: from physical processes to a dynamic model [thesis]. Bot; 1983.

[13] Van Henten, E. Greenhouse climate management: an optimal control approach; Van Henten; 1994; p.

[14] Taki, M.; Ajabshirchi, Y.; Ranjbar, S. F.; Rohani, A.; Matloobi, M. Modeling and experimental validation of heat transfer and energy consumption in an innovative greenhouse structure. Information Processing in Agriculture. 2016; 3: 157-174 p., doi:https://doi.org/10.1016/j.inpa.2016.06.002.

[15] Boulard, T.; Wang, S. Experimental and numerical studies on the heterogeneity of crop transpiration in a plastic tunnel. Computers and Electronics in agriculture. 2002; 34: 173-190 p.

[16] Bartzanas, T.; Boulard, T.; Kittas, C. Effect of vent arrangement on windward ventilation of a tunnel greenhouse. Biosystems Engineering. 2004; 88: 479-490 p.

[17] Madjoubi, H.; Boulard, T.; Fatnassi, H.; Senhaji, A.; Elbahi, S.; Demrati, H.; Mouqallid, M.; Bouirden, L. Canary greenhouse CFD nocturnal climate simulation. 2016: p.

[18] Majdoubi, H.; Boulard, T.; Fatnassi, H.; Bouirden, L. Airflow and

microclimate patterns in a one-hectare Canary type greenhouse: an experimental and CFD assisted study. Agricultural and Forest Meteorology. 2009; 149: 1050-1062 p.

[19] Fatnassi, H.; Boulard, T.; Poncet, C.; Chave, M. Optimisation of greenhouse insect screening with computational fluid dynamics. Biosystems Engineering. 2006; 93: 301-312 p.

[20] Chen, J.; Xu, F.; Tan, D.; Shen, Z.; Zhang, L.; Ai, Q. A control method for agricultural greenhouses heating based on computational fluid dynamics and energy prediction model. Applied Energy. 2015; 141: 106-118 p.

[21] Jarvis, P. The interpretation of the variations in leaf water potential and stomatal conductance found in canopies in the field. Philosophical Transactions of the Royal Society of London. B, Biological Sciences. 1976; 273: 593-610 p.

[22] Fidaros, D.; Baxevanou, C.; Bartzanas, T.; Kittas, C. Numerical simulation of thermal behavior of a ventilated arc greenhouse during a solar day. Renewable Energy. 2010; 35: 1380-1386 p.

[23] Ali, H.B.; Bournet, P.-E.; Cannavo, P.; Chantoiseau, E. Development of a CFD crop submodel for simulating microclimate and transpiration of ornamental plants grown in a greenhouse under water restriction. Computers and Electronics in Agriculture. 2018; 149: 26-40 p.

[24] Kacira, M.; Sase, S.; Okushima, L. Effects of side vents and span numbers on wind-induced natural ventilation of a gothic multi-span greenhouse. Japan Agricultural Research Quarterly: JARQ. 2004; 38: 227-233 p.

[25] Baeza, E.; Perez-Parra, J.; Lopez, J.; Montero, J. CFD simulation of natural ventilation of a parral greenhouse with a baffle device below the greenhouse

vents. In Proceedings of International Symposium on High Technology for Greenhouse System Management: Greensys 2007 801; 885-892 p.

[26] Flores-Velázquez, J.; Montero, J.; Baeza, E.; Lopez, J.; Pérez-Parra, J.; Bonachela, S. Analysis of mechanical ventilation in a three-span greenhouse using computational fluid dynamics (CFD). In Proceedings of International Symposium on High Technology for Greenhouse Systems: GreenSys 2009 893; 653-660 p.

[27] Flores-Velazquez, J.; Montero, J.I.; Baeza, E.J.; Lopez, J.C. Mechanical and natural ventilation systems in a greenhouse designed using computational fluid dynamics. International Journal of Agricultural and Biological Engineering. 2014; 7: 1 p.

[28] Roy, J.; Fatnassi, H.; Boulard, T.; Pouillard, J.-B.; Grisey, A. CFD determination of the climate distribution in a semi closed greenhouse with air cooling. In Proceedings of International Symposium on New Technologies and Management for Greenhouses-GreenSys 2015 1170; 103-110 p.

[29] Flores-Velázquez, J.; Vega-García, M. Regional management of the environment in a zenith greenhouse with computational fluid dynamics (CFD). Ingeniería Agrícola y Biosistemas. 2019; 11: p.

[30] Molina-Aiz, F.; Valera, D.; Pena, A.; Alvarez, A.; Gil, J. Analysis of the effect of rollup vent arrangement and wind speed on Almería-type greenhouse ventilation performance using computational fluid dynamics. In Proceedings of International Symposium on Greenhouse Cooling 719; 173-180 p.

[31] Bournet, P.; Khaoua, S.O.; Boulard, T.; Migeon, C.; Chasseriaux, G. Effect of roof and side opening combinations on

the ventilation of a greenhouse using computer simulation. Transactions of the ASABE. 2007; 50: 201-212 p.

[32] Bartzanas, T.; Katsoulas, N.; Kittas, C.; Boulard, T.; Mermier, M. The effect of vent configuration and insect screens on greenhouse microclimate. International Journal of Ventilation. 2005; 4: 193-202 p.

[33] Majdoubi, H.; Boulard, T.; Hanafi, A.; Fatnassi, H.; Demrati, H.; Bekkaoui, A.; Nya, M.; Bouirden, L. Determination and analysis of air exchange rate in a large greenhouse equipped with insect proof net. Acta horticulturae. 2007; 747: 151 p.

[34] Chen, J.; Cai, Y.; Xu, F.; Hu, H.; Ai, Q. Analysis and optimization of the fan-pad evaporative cooling system for greenhouse based on CFD. Advances in Mechanical Engineering. 2014; 6: 712740 p.

[35] Fidaros, D.; Baxevanou, C.; Bartzanas, T.; Kittas, C. Flow Characteristics and temperature patterns in a fan ventilated greenhouse. In Proceedings of International Workshop on Greenhouse Environmental Control and Crop Production in Semi-Arid Regions 797; 123-129 p.

[36] Baxevanou, C.; Fidaros, D.; Bartzanas, T.; Kittas, C. Numerical simulation of solar radiation, air flow and temperature distribution in a naturally ventilated tunnel greenhouse. Agricultural Engineering International: CIGR Journal. 2010; 12: 48-67 p.

[37] Ortíz-Vázquez, I.C.; Irene, R.-M.L.; Pérez-Robles, J.F.; Soto-Zarazúa, G.; Rico-García, E.; De la Torre-Gea, G.A. Analysis of large commercial greenhouses in warm climates using cfd and bayesian networks. Journal of Global Ecology and Environment. 2016; 5: 91-96 p.

[38] Boulard, T.; Roy, J.-C.; Pouillard, J.-B.; Fatnassi, H.; Grisey, A. Modelling of micrometeorology, canopy transpiration and photosynthesis in a closed greenhouse using computational fluid dynamics. Biosystems Engineering. 2017; 158: 110-133 p.

[39] Rezvani, S.M.-e. Optimization of ventilation and simulation of transpiration in Hamedan greenhouses with computational fluid dynamics and energy balance [thesis]. Iran, Hamedan: Bu-Ali Sina; 2020.

[40] Roy, J.C.; Boulard, T.; KITTAS, C.; Wang, S. Convective and ventilation transfers in greenhouses, part 1: the greenhouse considered as a perfectly stirred tank. Biosystems Engineering. 2002; 83: 1-20 p.

[41] Piscia, D.; Montero, J.I.; Baeza, E.; Bailey, B.J. A CFD greenhouse night-time condensation model. Biosystems Engineering. 2012; 111: 141-154 p.

[42] Van Beveren, P.; Bontsema, J.; Van Straten, G.; Van Henten, E. Minimal heating and cooling in a modern rose greenhouse. Applied energy. 2015; 137: 97-109 p.

[43] Van Beveren, P.; Bontsema, J.; Van Straten, G.; Van Henten, E. Optimal control of greenhouse climate using minimal energy and grower defined bounds. Applied Energy. 2015; 159: 509-519 p.

[44] Kindelan, M. Dynamic Modeling of Greenhouse Environment. Transactions of the ASABE. 1980; 23: 1232-1239 p.

[45] Bot, G. A validated physical model of greenhouse climate. Engineering and Economic Aspects of Energy Saving in Protected Cultivation 245. 1988: 389-396 p.

[46] De Zwart, H. Analyzing energy-saving options in greenhouse cultivation using a simulation model [thesis].

Wageningen: Wageningen University & Research; 1996.

[47] Vanthoor, B.; Stanghellini, C.; Van Henten, E.J.; De Visser, P. A methodology for model-based greenhouse design: Part 1, a greenhouse climate model for a broad range of designs and climates. Biosystems Engineering. 2011; 110: 363-377 p.

[48] Mobtaker, H.G.; Ajabshirchi, Y.; Ranjbar, S.F.; Matloobi, M. Solar energy conservation in greenhouse: Thermal analysis and experimental validation. Renewable Energy. 2016; 96: 509-519 p.

[49] Yildiz, I.; Stombaugh, D. Dynamic modeling of microclimate and environmental control strategies in a greenhouse coupled with a heat pump system. In Proceedings of III International Symposium on Models for Plant Growth, Environmental Control and Farm Management in Protected Cultivation 718; 331-340 p.

[50] Salazar-Moreno, R.; Irineo, L.; Sánchez Cruz, A.C. Dynamic energy balance model in a greenhouse with tomato cultivation: simulation, calibration and evaluation. Revista Chapingo Serie Horticultura. 2019; 25: p.

[51] Joudi, K.A.; Farhan, A.A. A dynamic model and an experimental study for the internal air and soil temperatures in an innovative greenhouse. Energy Conversion and Management. 2015; 91: 76-82 p.

[52] Challa, H. Crop models for greenhouse production systems. In Proceedings of IV International Symposium on Models for Plant Growth and Control in Greenhouses: Modeling for the 21st Century-Agronomic and 593; 47-53 p.

[53] Jamison, H. Dynamic Modeling Of Tree Growth And Energy Use In A Nursery Greenhouse Using Matlab And Simulink; 2006.

[54] Shamshiri, R. Measuring optimality degrees of microclimate parameters in protected cultivation of tomato under tropical climate condition. Measurement. 2017; 106: 236-244 p.

[55] Shamshiri, R.R.; Mahadi, M.R.; Thorp, K.R.; Ismail, W.I.W.; Ahmad, D.; Man, H.C. Adaptive management framework for evaluating and adjusting microclimate parameters in tropical greenhouse crop production systems. Plant Engin. 2017: 167-191 p.

[56] Shamshiri, R.R.; Jones, J.W.; Thorp, K.R.; Ahmad, D.; Che Man, H.; Taheri, S. Review of optimum temperature, humidity, and vapour pressure deficit for microclimate evaluation and control in greenhouse cultivation of tomato: a review. International agrophysics. 2018; 32: 287-302 p.

[57] Heuvelink, E. Evaluation of a dynamic simulation model for tomato crop growth and development. Annals of Botany. 1999; 83: 413-422 p.

[58] Abreu, P.; Meneses, J.; Gary, C. Tompousse, a model of yield prediction for tomato crops: calibration study for unheated plastic greenhouses. In Proceedings of XXV International Horticultural Congress, Part 9: Computers and Automation, Electronic Information in Horticulture 519; 141-150 p.

[59] Jones, J.W.; Dayan, E.; Allen, L.; Van Keulen, H.; Challa, H. A dynamic tomato growth and yield model (TOMGRO). Transactions of the ASAE. 1991; 34: 663-0672 p.

[60] Dimokas, G.; Tchamitchian, M.; Kittas, C. Calibration and validation of a biological model to simulate the development and production of tomatoes in Mediterranean greenhouses during winter period. biosystems engineering. 2009; 103: 217-227 p.

[61] Gallardo, M.; Thompson, R.; Rodríguez, J.; Rodriguez, F.; Fernández,

M.; Sánchez, J.; Magán, J. Simulation of transpiration, drainage, N uptake, nitrate leaching, and N uptake concentration in tomato grown in open substrate. Agricultural Water Management. 2009; 96: 1773-1784 p.

[62] Vanthoor, B.; Van Henten, E.; Stanghellini, C.; De Visser, P. A methodology for model-based greenhouse design: Part 3, sensitivity analysis of a combined greenhouse climate-crop yield model. Biosystems engineering. 2011; 110: 396-412 p.

[63] Evers, J.B.; Letort, V.; Renton, M.; Kang, M. Computational botany: advancing plant science through functional–structural plant modelling. Oxford University Press US: 2018.

[64] Evers, J.B. Simulating crop growth and development using functional-structural plant modeling. In Canopy photosynthesis: from basics to applications, Springer; 2016. 219-236 p. ^pp.

[65] Louarn, G.; Song, Y. Two decades of functional–structural plant modelling: now addressing fundamental questions in systems biology and predictive ecology. Annals of Botany. 2020; 126: 501-509 p.

[66] Vanthoor, B.; De Visser, P.; Stanghellini, C.; Van Henten, E. A methodology for model-based greenhouse design: Part 2, description and validation of a tomato yield model. Biosystems engineering. 2011; 110: 378-395 p.

[67] Vanthoor, B.H.; Gazquez, J.C.; Magan, J.J.; Ruijs, M.N.; Baeza, E.; Stanghellini, C.; van Henten, E.J.; de Visser, P.H. A methodology for model-based greenhouse design: Part 4, economic evaluation of different greenhouse designs: A Spanish case. biosystems engineering. 2012; 111: 336-349 p.

[68] Guo, Y.; Fourcaud, T.; Jaeger, M.; Zhang, X.; Li, B. Plant growth and

architectural modelling and its applications. Annals of botany. 2011; 107: 723-727 p.

[69] Vos, J.; Evers, J.B.; Buck-Sorlin, G. H.; Andrieu, B.; Chelle, M.; De Visser, P. H. Functional–structural plant modelling: a new versatile tool in crop science. Journal of experimental Botany. 2010; 61: 2101-2115 p.

[70] Zhang, N. From leaf to crop: quantifying photosynthesis responses of two flower crops [thesis]. Wageningen University; 2019.

[71] Zhang, N.; Van Westreenen, A.; Evers, J.B.; Anten, N.P.; Marcelis, L.F. Quantifying the contribution of bent shoots to plant photosynthesis and biomass production of flower shoots in rose (Rosa hybrida) using a functional–structural plant model. Annals of botany. 2020; 126: 587-599 p.

[72] Zhang, Y.; Henke, M.; Li, Y.; Yue, X.; Xu, D.; Liu, X.; Li, T. High resolution 3D simulation of light climate and thermal performance of a solar greenhouse model under tomato canopy structure. Renewable Energy. 2020; 160: 730-745 p.

[73] Szanto, C. In search of the optimal greenhouse tomato row orientation using functional-structural plant modeling, with focus on stomatal conductance [thesis]. Netherlands: Wageningen Agricultural University; 2016.

[74] Buck-Sorlin, G.; de Visser, P.H.; Henke, M.; Sarlikioti, V.; van der Heijden, G.W.; Marcelis, L.F.; Vos, J. Towards a functional–structural plant model of cut-rose: simulation of light environment, light absorption, photosynthesis and interference with the plant structure. Annals of Botany. 2011; 108: 1121-1134 p.

[75] Wiechers, D.; Kahlen, K.; Stützel, H. Dry matter partitioning models for the

simulation of individual fruit growth in greenhouse cucumber canopies. Annals of Botany. 2011; 108: 1075-1084 p.

[76] Evers, J. The Digital Twin project Virtual Tomato Crops (VTC). Availabe online: https://www.wur.nl/en/sh ow/The-Digital-Twin-project-Virtual-Tomato-Crops.htm (accessed on 15/01/ 2015).

[77] R Shamshiri, R.; Kalantari, F.; Ting, K.; Thorp, K.R.; Hameed, I.A.; Weltzien, C.; Ahmad, D.; Shad, Z.M. Advances in greenhouse automation and controlled environment agriculture: A transition to plant factories and urban agriculture. 2018: p.

[78] R Shamshiri, R.; Weltzien, C.; Hameed, I.A.; J Yule, I.; E Grift, T.; Balasundram, S.K.; Pitonakova, L.; Ahmad, D.; Chowdhary, G. Research and development in agricultural robotics: A perspective of digital farming. 2018: p.

[79] Shamshiri, R.R.; Bojic, I.; van Henten, E.; Balasundram, S.K.; Dworak, V.; Sultan, M.; Weltzien, C. Model-based evaluation of greenhouse microclimate using IoT-Sensor data fusion for energy efficient crop production. Journal of Cleaner Production. 2020; 263: 121303 p.