

# Advances in greenhouse automation and controlled environment agriculture: A transition to plant factories and urban agriculture

Redmond Ramin Shamshiri<sup>1\*</sup>, Fatemeh Kalantari<sup>2</sup>, K. C. Ting<sup>3</sup>, Kelly R. Thorp<sup>4</sup>,  
Ibrahim A. Hameed<sup>5</sup>, Cornelia Weltzien<sup>6</sup>, Desa Ahmad<sup>1</sup>, Zahra Mojgan Shad<sup>7</sup>

(1. Smart Farming Technology Research Center, Department of Biological and Agricultural Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400, Serdang, Selangor, Malaysia; 2. Department of Landscape Architecture, Faculty of Design and Architecture, Universiti Putra Malaysia, 43400, Serdang, Selangor, Malaysia; 3. Department of Agricultural and Biological Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA; 4. United States Department of Agriculture, Agricultural Research Service, U.S. Arid-Land Agricultural Research Center, Maricopa, AZ 85138, USA; 5. Dept. of ICT and Natural Sciences, Faculty of Information Technology and Electrical Engineering, Norwegian University of Science and Technology(NTNU), Larsgårdsveien 2, NO-6009 Ålesund, Norway; 6. Leibniz Institute for Agricultural Engineering and Bioeconomy, Max-Eyth-Allee 100, 14469 Potsdam-Bornim, Germany; 7. Adaptive AgroTech Consultancy International, CA 93955, USA)

**Abstract:** Greenhouse cultivation has evolved from simple covered rows of open-fields crops to highly sophisticated controlled environment agriculture (CEA) facilities that projected the image of plant factories for urban agriculture. The advances and improvements in CEA have promoted the scientific solutions for the efficient production of plants in populated cities and multi-story buildings. Successful deployment of CEA for urban agriculture requires many components and subsystems, as well as the understanding of the external influencing factors that should be systematically considered and integrated. This review is an attempt to highlight some of the most recent advances in greenhouse technology and CEA in order to raise the awareness for technology transfer and adaptation, which is necessary for a successful transition to urban agriculture. This study reviewed several aspects of a high-tech CEA system including improvements in the frame and covering materials, environment perception and data sharing, and advanced microclimate control and energy optimization models. This research highlighted urban agriculture and its derivatives, including vertical farming, rooftop greenhouses and plant factories which are the extensions of CEA and have emerged as a response to the growing population, environmental degradation, and urbanization that are threatening food security. Finally, several opportunities and challenges have been identified in implementing the integrated CEA and vertical farming for urban agriculture.

**Keywords:** smart agriculture, greenhouse modelling, urban agriculture, vertical farming, automation, internet of things (IoT), wireless sensor network, plant factories

**DOI:** 10.25165/ijabe.20181101.3210

**Citation:** Shamshiri R R, Kalantari F, Ting K C, Thorp K R, Hameed I A, Weltzien C, et al. Advances in greenhouse automation and controlled environment agriculture: A transition to plant factories and urban agriculture. Int J Agric & Biol Eng, 2018; 11(1): 1–22.

## 1 Introduction

Closed-field agriculture is experiencing a breakthrough

**Received date:** 2017-01-15 **Accepted date:** 2018-01-26

**Biographies:** **Fatemeh Kalantari**, PhD, research interests: vertical farming, Email: Fatimah.kalantari@AdaptiveAgroTech.com; **K. C. Ting**, Professor, research interests: controlled environment plant production systems, Email: kcting@illinois.edu; **Kelly R. Thorp**, Research Agricultural Engineer, research interests: agroecosystem modeling, remote sensing, precision agriculture, irrigation management, plant phenomics, Email: kelly.thorp@ars.usda.gov; **Ibrahim A. Hameed**, PhD, Associate Professor, research interests: machine learning, AI, optimisation and robotics, Email: ibib@ntnu.no; **Cornelia Weltzien**, PhD, Professor, research interests: mechanical engineering, control systems and agricultural engineering, Email: CWeltzien@atb-potsdam.de; **Desa Ahmad**, PhD, Professor, research interests: soil machine mechanics, agricultural machinery engineering, agricultural mechanization, controlled environment and smart farming, Email: desa@upm.edu.my; **Zahra Mojgan Shad**, Master, research interests: food science technology, Email: m.shad@adaptiveagrotech.com.

**\*Corresponding author:** **Redmond Ramin Shamshiri**, PhD, research interests: control systems, simulation and modeling. Department of biological and agricultural engineering, Faculty of engineering, Universiti Putra Malaysia, 43400, Serdang, Selangor, Malaysia. Tel: +60-3894-68472, Fax: +60-386567099, Email: raminshamshiri@upm.edu.my.

transition driven by the advances in precision technology, data processing and smart farming. Protected cultivations have changed from simple covered greenhouse structures to high-tech plant factories that optimize the productivity of the plants and human labour. A modern greenhouse operates as a system, therefore, it is also referred to as controlled environment agriculture (CEA), controlled environment plant production system (CEPPS), or Phytomation systems<sup>[1]</sup>. These structures use natural or artificial light within which optimum growth conditions is intended to achieve for producing horticultural crops, or for plant research programs. They also offer greater predictability, reduce the cost of production and increase crop yields. A comprehensive history of greenhouses in the past three decades can be found in the works of [2-6]. Examples of earlier works in automation and computer control of greenhouse environment are showed in [7-9]. Previous studies on greenhouse engineering during the 1990s have been reviewed by Hanan<sup>[10]</sup> and Critten and Bailey<sup>[11]</sup>.

The United Nations has predicted that by 2050, more than two-thirds of the nine billion world population will live in the cities. Securing the supply chain of fresh fruits and vegetables in this new scenario will be an overwhelming challenge. If properly designed,

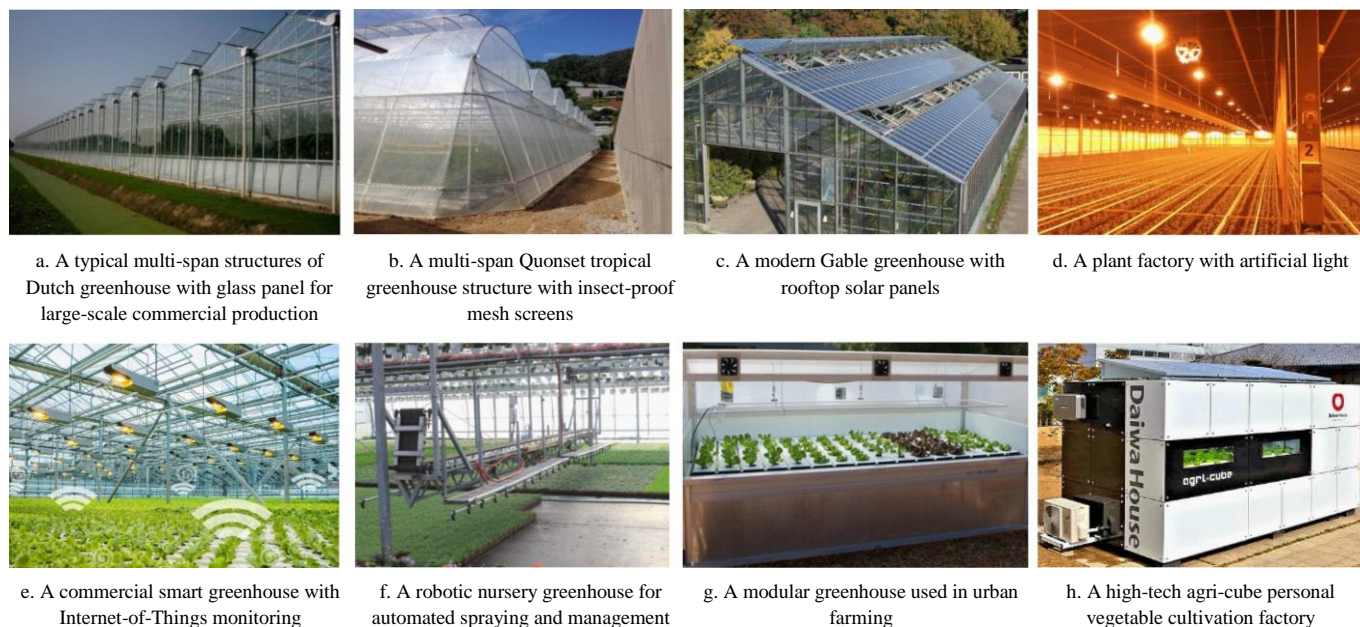
managed, and operated, CEA by means of agri-cubes and plant factories can significantly contribute to this context for the year-round production of fresh vegetables in urban areas. For such a system to operate successfully and achieve its production objectives, attention needs to be paid to the technical aspects of automation (A), culture (C), environment (E) and system (SYS). Ting et al.<sup>[1]</sup> defined ACESYS terms as follow: Automation is the processing of information and execution of tasks for operation of CEA through computerized instrumentations and various control algorithms that might include decision support programs and artificial intelligence. The cultural and environmental factors comprise cultivation techniques, plants characteristics, microclimate requirements and growth responses. It also contains morphological and physiological conditions such as “multiplication, rooting, transplanting, pruning, water and nutrient delivery, pesticide application, harvesting, post-harvest processing, etc”. Ting et al.<sup>[1]</sup> stated that “Systems analysis and integration is a methodology that starts with the definition of a system and its goals, and leads to the conclusion regarding the system’s workability, productivity, reliability, and other performance indicators.” Research trends in this field are toward innovative methods for shifting from conventional greenhouses to smart controlled environments that benefit from natural resources for eliminating deleterious external conditions. The ultimate objective in this regard would be achieving high yield and high-quality fruits at minimum possible cost.

Innovations in the low-cost and low-power consumption sensors and instrumentations, communication devices, data processing and mobile applications, along with the technological advances in the design structures, simulation models, and horticultural engineering have provided the state-of-the-art facilities that are shifting the traditional CEA to plant factories for urban farming. This paper begins with a summary of several reviewed literature in Section 2 on the advances in greenhouse covering materials, artificial light, and the efficiency of the microclimate controller for a viable CEA system. This part aimed to investigate the effects of the existing and new covering materials on the resulting microclimate (including influencing factors and their interactions with cultural practices), plants growth, and yield. Modeling of CEA, as well as object-oriented automation-culture-environment system analysis that is presented in the works of Ting et al.<sup>[1]</sup> provide a systematic approach for a better understanding of these influencing factors. These findings and their implications in a modern CAE such as plant factories and agri-cubes are further discussed in Section 5. After that, environmental monitoring and perception by means of wireless sensor networks (WSN) and internet of things-based (IoT-based) platforms have been demonstrated and reviewed as an essential part of an automation system. In our opinion, the three biggest challenges for the development of an efficient and viable CEA system are the creation of automation levels for energy management, reduction of environmental impact, and maximizing use of natural resources. A comprehensive review of the advances in environmental control methods, energy optimization models, prediction tools, and decision support systems are provided in Section 4. Specifically, the applications of different high-level algorithms for the most efficient microclimate control solutions are highlighted in Section 4.1. These control methods and automation phases have been

reviewed to illustrate how each part can facilitate achieving the overall objectives of a CEA. A summary of some of the research works in the past decade on energy analysis, artificial intelligence, and simulation models with applications in different aspects of greenhouse production are presented in Sections 4.2 and 4.3. A substantial amount of research has been done on individual aspects of automation, culture, and environment, as well as their combination, however improvements of CEA also require decision support systems (DSS) and assessment tools for long-term risk management by accurately determining the interactions between climate parameters and growth responses prior to the actual cultivation<sup>[12]</sup>. To identify technological pathways for energy efficient CEA, a survey was performed in Section 4.4 to highlight some of the improved solutions based on decision support systems for energy management strategies in the commercial greenhouses. In Section 5, the research covered urban agriculture and the development of plant factories and vertical farming which is growing rapidly in the East and Southeast Asia, most noticeably in Japan, South Korea, Taiwan Province of China, and Malaysia, and reviewed several conceptual designs such as the rooftop greenhouses to highlight how various research and educational institutes, real estate developers, and construction companies are involved in the emerged opportunities.

## 2 Considerations for viability

Several factors to be considered in designing of a viable greenhouse system for producing year-round crops and vegetables are the structure frame, landscape, topography, soil, climate conditions, microclimate control system, light condition, intercepted solar radiation, windbreaks, the availability of electricity, roadways, and labor force. Other conditions that should also be taken into account for an efficient large-scale commercial greenhouse production<sup>[13,14]</sup> are the environment, economic and social factors. For example, a modern greenhouse structure might be constructed within a commercial building or near commercial or residential lands. Some of the most popular greenhouse structures and CEA are presented in Figure 1. There are numerous experimental and analytical research works that address how environmental parameters inside a greenhouse is affected by the structural design and shape, volume size, dimensions, plants density, covering films, structure material, wind speed, geographical orientation, and most importantly the microclimate control system. For example, in regions where solar radiation or ambient air temperatures are high, several design factors for optimum air exchange such as the ratio of the area of the vent openings to the ground area covered by the greenhouse, the ratio of the greenhouse volume to the floor area, and the vertical distance between the air inlets and air outlets can significantly improve the ventilation performance. Optimization of vent configuration by evaluating greenhouse and plant canopy ventilation rates under wind-induced ventilation has been studied by Kacira et al.<sup>[15]</sup>. This section provides a summary of the research works that have addressed improvements in covering materials, and microclimate control systems. To avoid overlapping of the contexts and maintain a consistent flow of the topics, we have covered the advances in structure design (i.e., rooftop greenhouses) as a separate subsection under urban agriculture.



Source: <http://thefutureofthings.com>.

Figure 1 Snapshot views of some of the most popular modern greenhouses and controlled environment agriculture

## 2.1 Covering materials

Considerations for greenhouses covering materials involve supporting foundation, shape and framing materials, geographical direction for optimal light entrance, the load of equipment, factors for static and dynamic loads (i.e., hanging plants, structure weight, and wind speed), dimension ratio, and volume. Greenhouses structures and covering can take different forms which can be used to surround the whole or a section of the cultivation area and space. The most dominant transparent materials in use are 2-3 mm glass panels, net-screen film, and 0.1 mm and 0.2 mm Polyethylene (PE) plastic films, and ultraviolet (UV) stabilized PE-films. Baudoin et al.<sup>[16]</sup> recommended that in order to obtain a reasonable heat rise of less than 4 °C in a glass-clad greenhouse, the airflow rate should be 0.04-0.05 m<sup>3</sup>/s of floor area (1 m<sup>2</sup>). Selection of covering material for a greenhouse depends on its application, the type of crop to be cultivated, and the climate condition of the region. It can vary from simple covers such as one layer plastic<sup>[17,18]</sup>, double-wall plastic<sup>[19,20]</sup>, and glass<sup>[21,22]</sup>, to fiberglass<sup>[23,24]</sup>, double-wall plastic, acrylic sheet<sup>[25]</sup>, polyethylene film<sup>[26-29]</sup>, polyvinyl chloride (PVC)<sup>[30]</sup>, copolymers<sup>[31]</sup>, Polycarbonate panels<sup>[32]</sup>, and selective transmission medium<sup>[33,34]</sup> for different spectral frequencies. Some of these materials are designed to trap energy inside the greenhouse and heats both plants zone and its surroundings. Detailed properties of these covering, as well as the quality assessments of their mechanical properties, have been addressed in detail by a study on the effects of cover diffusive properties on the components of greenhouse solar radiation<sup>[34]</sup>.

Condensation, radiation transmittance and diffusing properties of different types of transmitting covering materials in greenhouses have been discussed by Pollet et al.<sup>[35]</sup>. Glazing materials allow shorter-wavelength radiation (i.e. visible light) to pass through, but long wavelength radiation such as infrared (heat) is trapped inside the greenhouse. A comparison between different greenhouse covering materials, including polyethylene film, photo-selective red color film, and insect-proof net for tomato cultivation during summer is available in the works of Arcidiacono et al.<sup>[36]</sup> and Hemming et al.<sup>[37]</sup> Jarquín-Enríquez et al.<sup>[38]</sup> studied the effects of

double layer plastic and flat glass cover on the lycopene accumulation and color index during tomato fruit ripening. They concluded that lycopene biosynthesis in tomato fruits was increased by the amount of light after the beginning of ripening growth stage. Studying the effect of greenhouse covering materials on the inside air temperature under tropical climate condition showed that while outside temperature was between 28 °C-33 °C, the temperature inside a polyethylene film covered greenhouse without environment control reached 68 °C-70 °C, leading to air vapor pressure deficit (VPD) of 4 kPa<sup>[39]</sup>. Al-Mahdouri et al.<sup>[40]</sup> evaluated optical properties and thermal performances of different greenhouse covering materials. The combinations of external climate conditions and type of greenhouse for the most appropriate application have been studied by Kempkes et al.<sup>[41]</sup> A computer application to measure geometric characterization and dimensions of insect-proof screens was designed by Álvarez et al.<sup>[42]</sup>. Polythene-clad greenhouses do not become as hot because of the transparency of the plastic to long-wave radiation that is transmitted back out of the greenhouse. Therefore, for a polythene-film covered greenhouse, the ventilation rate can be reduced to 0.03-0.04 m<sup>3</sup>/s of floor area (1 m<sup>2</sup>)<sup>[43]</sup>. With greenhouse shading, the amount of solar radiation and light intensity reaching the plants is restricted, creating a closed difference between air temperature inside and outside the greenhouse. Shading also decreases leaf surface temperature significantly. According to Glenn et al.<sup>[44]</sup>, while a 20% to 80% light reduction can be expected depending on the shading materials, the sufficient light reduction for most greenhouse applications is between 30% and 50%. Hassanien and Li<sup>[45]</sup> investigated the microclimate parameters and growth responses of lettuce plants inside a greenhouse that was shaded with semi-transparent mono-crystalline silicon double glazing photovoltaic panels (STPV). The STPV panels of their study accounted for 20% of the greenhouse roof area, and showed that the combination of STPV and polyethylene cover decreased the solar radiation by 35% to 40% compared to the use of polyethylene cover. They also showed that the STPV shading decreased the air temperature by

1 °C-3 °C but did not have any significant effect on the relative humidity, fresh weight, leaf area and the chlorophyll contents under natural ventilation.

Protected cultivation of Solanaceous crops such as tomatoes and peppers by means of Screen-houses operating on natural ventilation is now a commonly practiced in tropical lowlands for reducing insect migration, the risk of damage by high rainfall, extreme solar radiation, and high wind speeds. In addition, by using insect-proof net covered greenhouse, the inside and outside temperature may remain similar, while temperature has been observed to be rising with the photo-selective film during summer. Studies showed that net-screen greenhouses have gained more popularity in tropical regions due to the potential of climate parameters that have optimality degrees close to the plants desired levels. Shamshiri<sup>[46]</sup> observed that under an insect-proof net-screen covered greenhouse operating on natural ventilation, the inside and outside air temperature remained close to each other, while the air temperature was found to increase inside two photo-selective film covered greenhouses (polycarbonate panel and a polyethylene covered) operating on evaporative cooling<sup>[39]</sup>. Shading nets ease the natural ventilation process and can protect plants from excessive sunlight, wind, and heavy rains. Lorenzo et al.<sup>[47]</sup> reported that movable shade under intense sunlight in Spain caused 10% increase in the marketable yield of greenhouse tomato. Other reports indicated that external and internal shading nets reduced horizontal and vertical gradients in air temperature compared with those without shading nets<sup>[48]</sup>. Results of a study on the effect of roof height of a large screen-house on the ventilation rate using one-dimensional computational model and preliminary measurements showed that increasing roof height by 2

m increases both temperature and humidity levels in the canopy layer<sup>[49]</sup>. Microclimate, air velocity, ventilation efficiency, and light transmittance are mainly influenced by the properties of the net-screen mesh and the greenhouse shape. While these structures enhance natural ventilation in hot and humid climate conditions, they still require strong shelters for protecting plants from extreme solar radiation, rain, and strong winds. The screen-house itself is an important pest protection device, provided it is equipped with fine mesh screens in all openings, and a double-door system.

## 2.2 Light control and artificial lights

The main approaches for controlling light level and the intercepted radiance in CEA are through planted density, shading screens, and artificial lights. Light condition and air temperature are the two most important environmental factors for plants growth. In fact, discussions about optimal air temperature without including light condition and plant evapotranspiration does not generate any useful data for maximizing yield and producing high-quality vegetable. Light and air temperature are intrinsically related and it is a well-known fact that one cannot be optimized without considering the other. For example, tomato quality, including yield, productivity and lycopene value is not only affected by the microclimate parameters and cultural experience, but with the Photosynthetic Photon Flux Density (PPFD). In fact, it is the optimal combination of air temperature, relative humidity, and light that will result in maximum yield (assuming that other factors such as CO<sub>2</sub>, soil pH, and nutrient are not limiting). A schematic diagram is presented in Figure 2 to illustrate the effects of light spectral, intensity and photoperiod on plant growth, along with a comparison between spectral power distribution of natural and artificial light sources, and the plant's response to irradiance level.

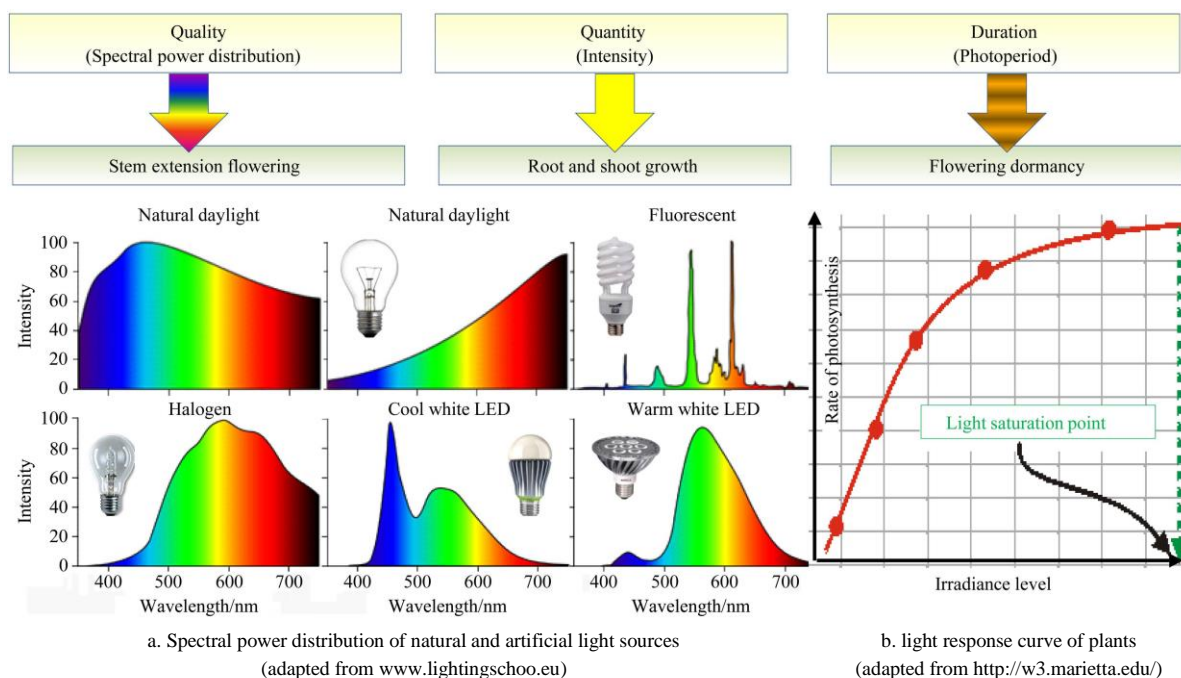


Figure 2 Comparison between spectral power distribution of natural and artificial light sources and light response curve of plants

The most common artificial light sources that are used in modern greenhouses and CEAs are incandescent/halogen lamps, discharge lamps (such as fluorescent light tubes, Metal Halide, and high-pressure sodium lamps), and the Light-emitting diodes (LEDs). Among these, LEDs have gained significant popularity in the research and development communities due to their

advantages such as cost efficiency, compact design, durability, light quality, and low thermal energy generation. Research on LEDs as a substitute for plant growth began in 1980s; however it was only after mid-2000s that they became economically feasible for large scale commercial production. These devices reduce the costs of electricity by using plant from effectual



transformation of electric power to directed light wavelengths. Moreover, the compact design of LEDs that located close to the plants, allows the structure of various layers of plant production to stack vertically in CEA, while decreasing the costs of cooling compared with other artificial light sources. Nowadays the functional costs of LEDs are a high-priority study and advance subject for upcoming greenhouse-based plant factories. In the case of tomatoes, shading affects biosynthesis and carotene level of lycopene. According to the study of Cockshull et al.<sup>[50]</sup>, plant factory yield will be reduced by 20% by utilizing a cover with 23% shade. Yields also will be enriched with color shaded in plant factories in hot weathers. Yet, color shades can be disadvantageous in areas with limited sunlight hours in cloudy and cold climates. In fact, choosing suitable planting density can increase crop water output and improve light capture. On the other hand, the planting density has an effect on the harvest of tomato in greenhouse growing system and evapotranspiration (ET)<sup>[51]</sup>. According to the reports of several studies, factors such as numbers of flowering, fruits location in per plant and single fruit weight were all lesser with more density of planting, therefore, resulting in lesser harvests<sup>[52-54]</sup>. In another study, Ilić et al.<sup>[55]</sup> showed that in the tomato factory, by using red shade netting techniques the lycopene content highly increased, however, these fruits had minor carotene content. Maximum production of tomato by percentages of covering are described under 40% by El-Aidy and El-Afry<sup>[56]</sup> and 35% by El-Gizawy et al.<sup>[57]</sup> Moreover, El-Gizawy et al.<sup>[57]</sup> claimed that by increasing

covering intensity, the production of tomato will increase up to 51%. The soil surface will lose its moisture in plants faster by absorbing the more radiant energy, but, the high density of tomato plants caused less radiation at the soil surface<sup>[52]</sup>.

### 2.3 Efficiency of microclimate controller

An efficient greenhouse requires environment control for air quality, **disease reduction**, **pest control**, and **nutrient and water uptake**. The inputs and outs of a greenhouse system are shown schematically in Figure 3. **The quality of air is governed by factors such as air and root-zone temperature, humidity, carbon dioxide, air movement, dust, odors and disease agents**. Other variables in the greenhouse environment that affect plant's life are light condition, soil feeding solution pH and electrical conductivity. These parameters and the problems associated with each have been extensively discussed by several textbooks, see for example Hochmuth and Hochmuth<sup>[58]</sup>, Cherie<sup>[59]</sup> and Jones<sup>[60]</sup>. Plant growth responses to other influencing factors and climate changes such as carbon dioxide and wind speed have been discussed in the textbook of Morison and Morecroft<sup>[61]</sup>. In general, microclimate parameters in a CEA are manipulated by passive and active ventilation, evaporative cooling techniques, shadings, and refrigeration dehumidification. **Several methods based on the Fans Assessment Numeration System (FANS) for evaluation of the ventilation performance and suggestions for the energy efficiency of greenhouse fans are presented in [62]**. It should be noted that the high operating costs of air-conditioners make them impractical for commercial application.

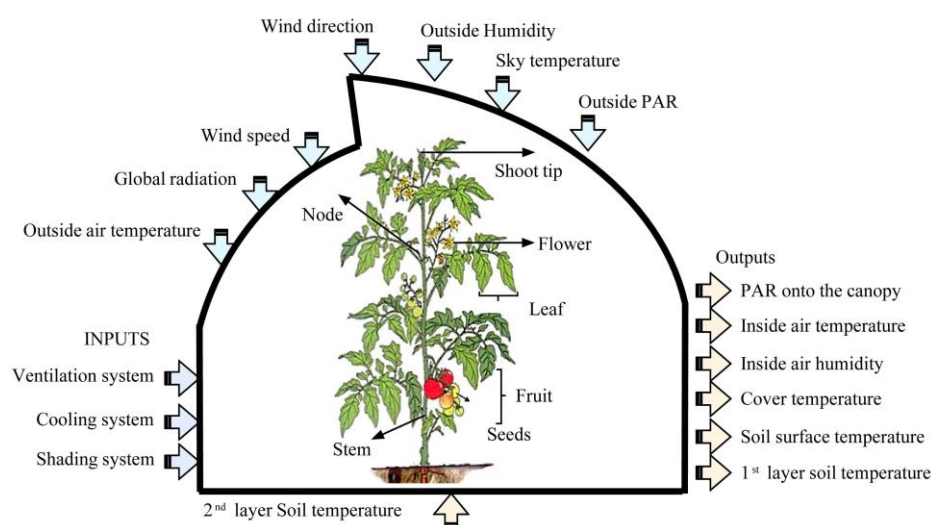


Figure 3 Inputs and outputs of controlled environment agriculture

The efficiency of active systems, i.e., fan and pad evaporative cooling, has been widely studied and modeled for modular greenhouses that use mechanical **ventilation**<sup>[63,64]</sup>, but research works on their use alongside natural ventilation in greenhouses in semiarid climates are narrow<sup>[65]</sup>. Reports showed that when ventilation fan belts were adjusted to the proper tension, the fan speed and airflow rate were respectively 13.1% and 30.1% higher than those of original belts<sup>[62]</sup>. The same study also reports that the daily average energy consumption for the **ventilation fan with** the original loose belts was 20.4% higher than that with the adjusted belts when the pad was not working, and 24.2% higher with pad working. There are theoretical and experimental studies which compare the effects of fogging and fixed shading systems on the Mediterranean greenhouse climate<sup>[66]</sup>; however, the assessment

of mobile shading is not well documented. In order to determine the size of fans and pads for evaporative cooling, the volume of the greenhouse needs to be calculated. An air exchange ( $\text{m}^3/\text{min}$ ) of 1 to 1.5 times of the greenhouse volume is recommended every minute<sup>[16]</sup>. The number of fans should be selected based on the air exchange and by taking into account that their placement should not be spaced more than 7.6 m apart. According to Duan et al.<sup>[67]</sup>, a properly operated typical swamp cooler has the potential to cool air within 3 °C to 4 °C of the wet-bulb temperature. These units cost less than air-conditioner and consume 60% to 80% less electricity; however, they are only practical for small greenhouses in hot dry regions. Another form of evaporative cooling is misting which reduces plant moisture loss and leaf transpiration by reducing its temperature due to evaporative cooling. Misting is

categorized into low-pressure and high-pressure (also known as fog-cooling). In fog-cooling systems, high-pressure water is passed through nozzles with orifice sizes usually less than 10  $\mu\text{m}$ . A fan then blows the extremely small droplets of water into greenhouse air and reduces temperature through an evaporative process. These systems are usually used in greenhouse cooling for seed germination and propagation. A major drawback of this method is that it creates high humidity climate inside canopies which facilitates the development of bacterial diseases, such as algae and botrytis. Several recommendations for obtaining better cooling results with misting are available in the work of Schnelle and Dole<sup>[68]</sup>. Low and high-pressure fogging systems in a naturally ventilated greenhouse have been studied and compared by Li and Willits<sup>[69]</sup>, suggesting that compared to the low-pressure fogging system, the average evaporation efficiency for the high-pressure system was at least 64% greater. Moreover, the cooling efficiency of the high-pressure system was at least 28% greater than for the low-pressure system. Determination of cooling efficiencies for misting and fogging systems is available in the work of Abdel-Ghany and Kozai<sup>[70]</sup>. The efficiency of an evaporative cooling system is calculated by

$$\eta = \frac{T_{out} - T_{cool}}{T_{out} - T_{wb}} \quad \text{as given in the ASABE standards}^{[71]}. \quad \text{Here, } T_{out}$$

is the outdoor air temperature,  $^{\circ}\text{C}$ ;  $T_{cool}$  is the temperature of air exiting the cooling pad,  $^{\circ}\text{C}$ , and  $T_{wb}$  is the wet-bulb temperature of the outside air,  $^{\circ}\text{C}$ .

Measurement and data analysis for greenhouse evaporative cooling are discussed in the work of Kittas et al.<sup>[72]</sup> A decrease in air temperature by 4  $^{\circ}\text{C}$  to 5  $^{\circ}\text{C}$  inside a greenhouse with pad-and-fan evaporative cooling is reported by Jain and Tiwari<sup>[73]</sup>. Performance of a two-stage pad cooling system in broiler houses was analyzed by Petek et al.<sup>[74]</sup> showing that the resulting air temperature and relative humidity were significantly lower than those of the traditional system. A thermal model for prediction of microclimate factors inside a greenhouse with mechanical ventilation and the evaporative cooling system was introduced by Willits<sup>[75]</sup>. Their results suggested that in the presence of evaporative cooling, increasing canopy size is more influential in reducing air temperature. They also concluded that without evaporative cooling pads, the ratio of energy used for transpiration to incoming solar energy (known as the evapotranspiration coefficient) is predicted to range from 1-75 for an outdoor air temperature of 36.8  $^{\circ}\text{C}$  and a humidity ratios of 3.3 g/kg, to 0.8  $^{\circ}\text{C}$  for an outdoor humidity ratio of 29.9 g/kg at the same air temperature. In another study, Max et al.<sup>[76]</sup> investigated the effects of greenhouse cooling methods, including mechanical ventilation and evaporative cooling, on yield and quality of tomato in tropical climates. It was found that the proportion of marketable yield was significantly higher in a net-screen covered greenhouse with mechanical ventilation, and the quantity of undersized and blossom-end rot affected fruits was reduced in polyethylene film covered greenhouse with the evaporative cooling method. The researchers then concluded that in regions with high relative humidity, evaporative cooling without customized adjustments for dehumidification will not improve closed-field production of tomato.

Passive cooling methods, including natural ventilation and shading, are widely practiced in greenhouses, especially those in tropical regions, by means of non-adjustable, manually adjustable,

or automatically controlled. Natural ventilation is caused by the stack effect, wind ventilation, or both. Ventilation for air temperature control is efficient only when outside air temperature of the greenhouse is less than inside. Some of the factors to be taken into account for designing of a proper naturally ventilated greenhouse are the location of the structure, insulation, ceiling slope and ventilation openings. Various references have concluded that using natural ventilation, it is more difficult to uniformly distribute fresh air in wider greenhouse structures<sup>[77,78]</sup>. A comprehensive review of ventilation systems is available in the works of Ganguly and Ghosh<sup>[79]</sup>. The air inlet and outlet size for natural ventilation are determined based on stack effect theory as expressed by the Equation (1). The steady-state heat balance for determination of maximum ventilation rate requires heat gains to be equal to heat losses and is given by Equation (2). This equation is used to determine: (i) the required ventilation rate to maintain a given inside temperature for a given heater capacity; (ii) the minimum outside temperature (balance temperature) to maintain the desired inside temperature without using supplemental heat ( $q_h=0$ ) at a given ventilation rate; and (iii) the size of heater required to maintain the desired inside temperature for a given ventilation rate and outside (design) temperature.

$$\frac{1}{A_i^2} = \frac{1}{A_o^2} = \frac{2g \cdot h \cdot H_p}{T_i(\rho \cdot S \cdot V + W)V^2} \quad (1)$$

$$q_s + q_m + q_{s0} + q_h = \left( \sum_c (AU)_c + FP + C_p \cdot \rho \cdot V \right) (t_i - t_o) \quad (2)$$

where,  $A_i$  is inlet size of natural ventilation,  $\text{m}^2$ ;  $A_o$  is outlet size of natural ventilation,  $\text{m}^2$ ;  $g$  is gravity=9.76,  $\text{m/s}^2$ ;  $h$  is height difference between inlet to outlet of natural ventilation, m;  $H_p$  is heat supplied to the greenhouse structure, W;  $T_i$  is absolute temperature in greenhouse,  $K=(^{\circ}\text{C} + 273)$ ;  $\rho$  is density of air in greenhouse, is equal to 1.175 at 25  $^{\circ}\text{C}$ ,  $\text{kg/m}^3$ ;  $S$  is specific heat of air,  $\text{J/(kg} \cdot ^{\circ}\text{C)}$ ;  $V$  is ventilation rate,  $\text{m}^3/\text{s}$ ;  $W$  is heat loss through greenhouse cover,  $\text{W/}^{\circ}\text{C}$ ;  $U$  is overall unit area thermal conductance of component,  $\text{W/(m}^2 \text{K)}$ ;  $A$  is area of structural component,  $\text{m}^2$ ;  $c$  is path of heat transfer, which may be a wall or roof component, m;  $P$  is the structure perimeter, m;  $F$  is an experimentally determined perimeter heat loss factor, the values of  $F$  for an un-insulated and unheated slab floor on grade range between 1.4 and 1.6 (depending on how low the ambient temperature is),  $\text{W/(m} \text{K)}$ ;  $C_p$  is specific heat of moist air,  $\text{J/(kg} \text{K)}$ ;  $V$  is volumetric airflow rate,  $\text{m}^3/\text{s}$ ;  $t_i$  is indoor temperature,  $^{\circ}\text{C}$ ;  $t_o$  is outdoor temperature,  $^{\circ}\text{C}$ .

### 3 Environment monitoring and perception

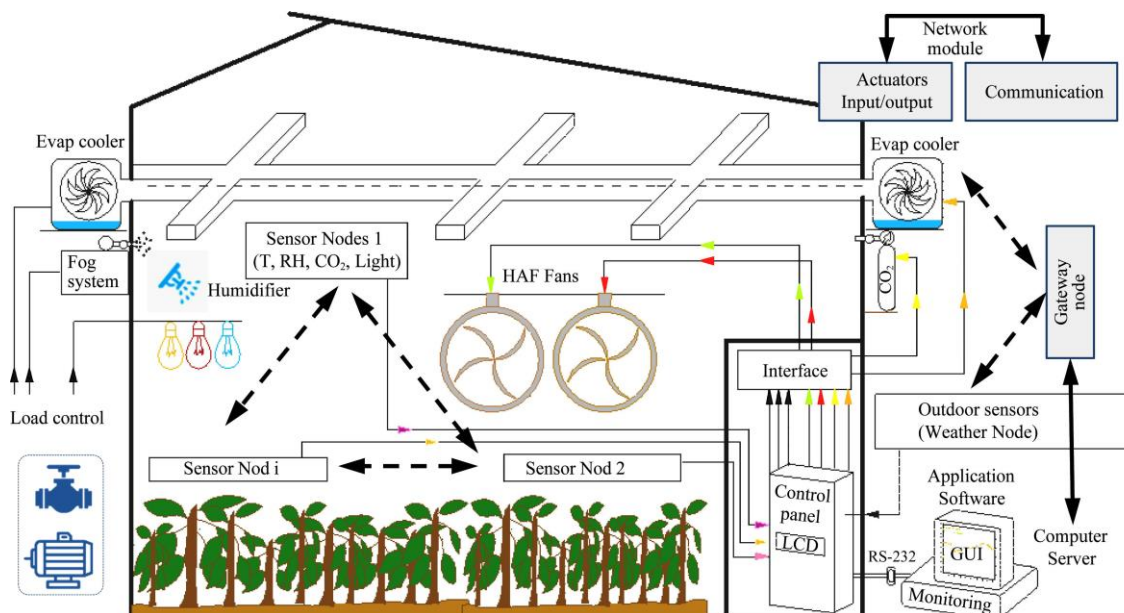
A review of the recent trends in greenhouse environmental monitoring shows that research and development in this field are shifting from offline systems to wireless and cloud-based data collection architectures. Various data acquisition platforms, either prototype or commercial, have been used for improving the performance of greenhouse production. Some of the most recent examples include web-based, cloud-based, IoT communication and control<sup>[80-83]</sup>, wireless sensor networks<sup>[84,85]</sup>, field-server based monitoring<sup>[86]</sup>, field router systems<sup>[87,88]</sup>, and distributed data acquisition with local control management<sup>[89,90]</sup>. A comprehensive comparison between the existing remote monitoring system in agricultural research is available in the work of Prima et al.<sup>[91]</sup> General components of a greenhouse environmental monitoring are shown in Figure 4. This section review two of the

most popular greenhouse monitoring frameworks, the wireless sensor networks (WSN), and the IoT based systems, which have redirected greenhouse measurement concentration to a new level for improving efficiency and viability.

### 3.1 Wireless sensor networks

Research and development in greenhouses in the early 2000s began to adopt wireless communication technology for monitoring, sending early warning messages, and remote control using

simplified rules. One of the earliest reports of WSN application in greenhouse environment monitoring can be found in the work of Serôdio et al.<sup>[92]</sup> The compact size, reliability, and cost-effectiveness of WSN modules, as well as flexibility for developing custom applications besides easy installation, have made this technology gain attention and popularity for monitoring and control in open-field<sup>[93,94]</sup> and in closed-field environment agriculture.



Source: www.AdaptiveAgroTech.com.

Figure 4 General components and instrumentations in a typical greenhouse environmental monitoring

An interesting application of WSN in greenhouse includes CO<sub>2</sub> management<sup>[95]</sup> and multipoint measurements of microclimate for monitoring spatial gradients and three-dimensional changes in parameters during the cultivation process<sup>[96]</sup>. For example, Ji et al.<sup>[97]</sup> developed a WSN for precision control of CO<sub>2</sub> fertilizer with an improved method for prediction of tomato photosynthetic rate. A computerized horticulture data management system that is addressed in [92] was developed by implementing WSN, controller area network (CAN), and several internet and email communication tools, and was able to support distributed data monitoring and control inside the greenhouse environment. Morais et al.<sup>[93]</sup> reported the architecture of a WSN platform called MPWiNodeZ, a mesh-type array of acquisition devices that was designed based on ZigBee multi-powered wireless acquisition device for the purpose of remote sensing applications in precision horticulture. A remarkable advantage of this platform is the power management capability that allows the system to continuously operate in large coverage areas where connection stability and power sources are a concern. A simple deterministic WSN based on IEEE 802.15.4 and XMesh protocol for online monitoring and control of air temperature and relative humidity with several sensors nodes that were placed inside the greenhouse in a uniform gridded topology is presented in the work of Pahuja et al.<sup>[98]</sup> The authors used a network health analyzer and found that while the data reliability was 100%, their network mean packet reliability was between 75%-100% due to the packet losses. This failure can be related to the canopy coverage and sensors occluded by the dense plantation which reduces the signal strength of the nodes. This network was integrated into a multiple inputs and

multiple outputs fuzzy logic based controller and an RS-485 actuator network to manipulate the greenhouse vapor pressure deficit. Prima et al.<sup>[91]</sup> developed and evaluated a simple and flexible remote environmental monitoring and control based on a cloud platform. They implemented a local-global management strategy supporting synchronization of online and offline system configuration, actuation, and offline management to respond to the unstable network connection in the rural area. They tested the functionality of their system during a 10-day data collection period for automated monitoring of soil moisture content and fertigation control in tomato cultivation. Their results showed that under unstable network, the system only had 0.78% error, and provided 99.2% in-range soil moisture content measurement, which shows the potential for long-term microclimate monitoring application in greenhouses.

An important consideration in designing of an efficient WSN for the greenhouse is the number of nodes, their location, distances between nodes, antenna and the operating frequency based on the greenhouse microclimate condition. Studies showed that radio wave propagation is strongly affected by the high greenhouse environment<sup>[99]</sup>. Several other connectivity issues with WSN in the greenhouse have been addressed in [100] using connection matrix to estimate the network connectivity in the disconnected spots. For this purpose, Chen et al.<sup>[100]</sup> established a remote monitoring system in an experimental greenhouse using ZigBee-based WSN which could monitor air temperature, humidity and light intensity as well as the wireless link quality. Their results showed that by adding long-distance backup routing nodes, network connectivity can be guaranteed in the spots having poor

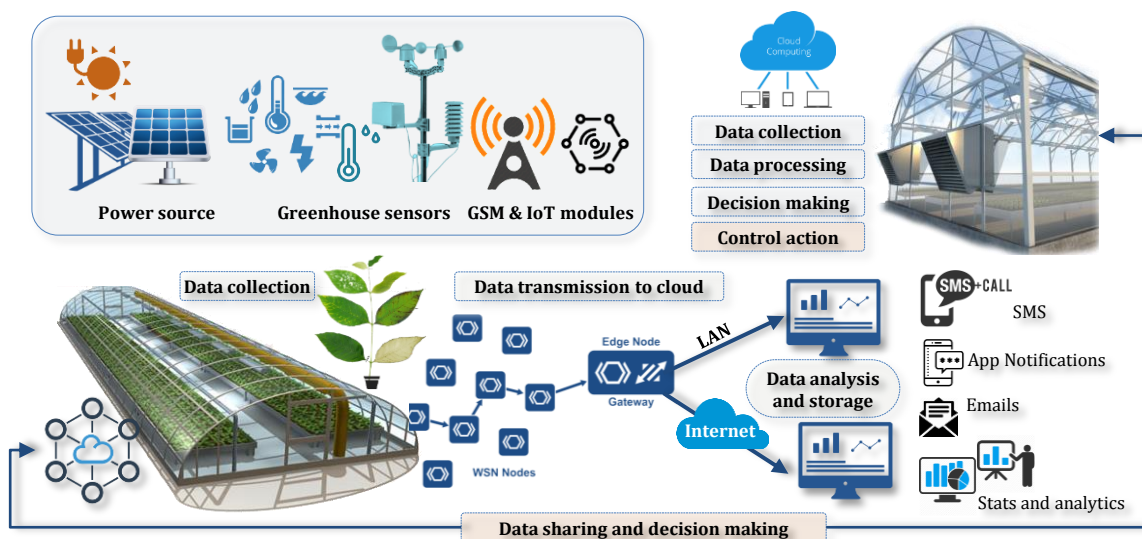


Received Signal Strength Indicator (RSSI), for example, situations with low energy and RSSI value of less than 100 dBm. Another ZigBee WSN application based on star and mesh network architecture for monitoring air temperature, relative humidity, and soil moisture content inside the greenhouse is available in the work of Zhou et al.<sup>[101]</sup> More recently, Azaza et al.<sup>[102]</sup> presented a smart type-2 fuzzy logic based control system to manage the greenhouse microclimate with attention to the effectiveness, the energy use and the production costs. They integrated an observer and smart automation system into the control process by using a wireless data monitoring platform enabling a distance data measurement. Their method also provided a real-time data access and building database that can be used for future enhancement of the system accuracy and decisions making. The efficiency of their proposed monitoring and control system was validated through a comparative study by

evaluating the energy saving (22%), and the water use (33%).

### 3.2 IoT-based monitoring

The traditional data monitoring techniques in greenhouse frequently suffer from lack of sharing and availability, great labor-intensity, low spatiotemporal resolution, a lack of data centralization, and organizational management in observing the environmental aspects of a greenhouse. The IoT offers an excellent opportunity not only in greenhouse environment monitoring but as a method for non-destructive quantification of physiological factors of the cultivated plants to be shared within a network of other greenhouse producers. The potential greenhouse applications of IoT cover a variety of scenarios. General components of a greenhouse environmental monitoring based in wireless sensor network and IoT concept are illustrated in Figure 5.



Source: [www.AdaptiveAgroTech.com](http://www.AdaptiveAgroTech.com).

Figure 5 General components of a greenhouse environmental monitoring based in wireless sensor network and IoT concept

The main element in the IoT is the network, which has made possible a breakthrough in data communication and sharing for greenhouse monitoring and control. It contains several physical items, software, and sensors that are linked with wires or wirelessly through standard communication protocols<sup>[103]</sup>. Both academic and industry sections have shown interest in greenhouse applications of IoT<sup>[104]</sup>. In fact, IoT has been used in many areas of researchers, such as: smart city<sup>[105]</sup>, agriculture<sup>[106,107]</sup> and healthcare<sup>[108-110]</sup>, and is changing the traditional farming observation approaches by quickly providing quantitative data with effective spatiotemporal resolution. For example, long-term past information collected by IoT applications can be an offer to a local greenhouse community to conduct combined pest and disease management agendas in order to stop spreading of the associated damages. These data can also improve cultural practices and decision making plans<sup>[107]</sup>. An application of this technology can be found in the work of Liao et al.<sup>[111]</sup> who developed an IoT monitoring system to simultaneously screen the growth condition of *Phalaenopsis* and the environmental features of an orchid plant factory. For example, Peng et al.<sup>[112]</sup> showed that by using a spectroscopic and spectrometer investigation can correctly provide the total of orchid chlorophyll.

Moreover, Lin and Hsu<sup>[113]</sup> applied a chlorophyll fluorometer in their study. They monitored the photosynthetic status of

*Phalaenopsis* under diverse lighting situations. Although the physiological analysis is often occupied manually, these examination approaches need tools with perfect accuracy to nondestructively degree physiological factors of orchids. Furthermore, because of the cost, farmers will not use highly precise tools to measure physiological factors of orchids. With scalability and flexibility of IoT, growers can have an excellent opportunity to meet such observing demands<sup>[109]</sup>.

## 4 Environmental control and energy optimization

This section reviews some of the recently published works on the advances in microclimate modeling and control, greenhouse energy analysis, predictions of yields and environmental parameters, optimization models, and decision support systems application for best cultivation practices.

### 4.1 Advances in microclimate control

Conventional microclimate control algorithms are designed based on a series of reference values known as set points. The controller then adjusts the outputs with implemented rules to achieve stability by minimizing the error between references and the inputs. The control of the microclimate in a greenhouse is a high-level task because of the number of involved variables that are coupled and interrelated, making a complex non-linear system.

Some of the earlier attempts to apply advanced control



techniques for greenhouse environment can be found in the works of Caponetto et al.<sup>[114]</sup>, Pan et al.<sup>[115]</sup>, Lin<sup>[116]</sup>, Castañeda-Miranda et al.<sup>[117]</sup> and Xu et al.<sup>[118]</sup> Recent advances in computer simulation and artificial intelligence have worked their way into greenhouse environment modeling and predictions. Identifications and modellings of different parameters in greenhouses have been topics of numerous research works that aimed at improving production efficiency (i.e., higher yield and quality, maximum return) by evaluating and adjusting microclimate parameters and modeling of micrometeorology<sup>[119,120]</sup>. The level of approaches vary from simple models and timer-based feedback controls<sup>[121,122]</sup> to more advanced solutions, such as model-free control strategy<sup>[123]</sup>, nonlinear control methods<sup>[124]</sup>, adaptive control and adaptive management framework<sup>[120,125]</sup>, robust<sup>[126]</sup>, optimal control<sup>[127-132]</sup>, energy balance models<sup>[133]</sup>, and model-based predictive control<sup>[134]</sup>. An important drawback in utilizing advanced control methods in a CEA is the difficulty in developing the dynamic model to simulate the behavior of the variables. Ultimately, the goal of any of these control systems is to minimize the input cost per unit of production and to increase the return by achieving high yield and quality.

The success of greenhouse systems analysis relies on the effective use of information. To meet these requirements, various control strategies based on complex algorithms of artificial intelligence have been discussed in the literature. For example, fuzzy systems have achieved significant results in the area of precision irrigation<sup>[135]</sup> and microclimate control. Several techniques and approaches have been presented, including inverting fuzzy model<sup>[136]</sup>, reconfigurable adaptive fuzzy fault-hiding control<sup>[137]</sup>, TakagiSugeno fuzzy modeling<sup>[138]</sup>, conventional fuzzy logic control for smart greenhouses<sup>[102]</sup>, and decentralized decoupling fuzzy logic controller<sup>[139]</sup>. These solutions have shown a more effective set-point tracking compared with the conventional PID controllers. For example, El-Madbouly et al.<sup>[137]</sup> designed an active fault-tolerant control system to fix of the device or sensor errors in weather system of a greenhouse. This control scheme involves a self-tuned fuzzy proportional-integral (PI) control scheme, a strong fault-hiding-based reconfigurable controller that can fix the faulty effects, and a reliable and sensitive observer-based fault detection and diagnosis (FDD) system for diverse kinds of errors in the presence of scheme disorderliness. A set of practical actuators and sensors were applied in this method to renovate the closed-loop consistency and also to confirm correct tracking of resource inputs. Azaza et al.<sup>[102]</sup> introduced a smart fuzzy logic based control scheme and upgraded by a special measure to the humidity relationship and temperature. Also, the scheme control was improved with wireless information observing platform for information routing and logging which prepares actual time of information entree.

#### 4.2 Energy analysis and optimization models

Energy management strategies for optimizing greenhouse cost<sup>[104]</sup> require a comprehensive research and knowledge and understanding of climate condition, greenhouse systems, and plants' requirements. Some of these research involves practicing innovative concepts of energy conservation and clean-energy using mathematical models<sup>[141,142]</sup>, determining energy load using building energy simulation models<sup>[143]</sup>, computational fluid dynamics method<sup>[119,144,145]</sup>, or providing optimal growth condition

with minimum environmental impacts<sup>[120,146,147]</sup>. Other researchers have proposed optimization methods for maximizing the returns. See for example the works<sup>[148]</sup> in which a dynamic model of a greenhouse tomato and the optimal control problem for the seasonal benefit of the grower has been presented. A formulation of the optimal control problem for minimizing energy input to the greenhouse with a dynamic energy balance was presented by van Beveren et al.<sup>[149]</sup> and later expanded in [150] to include humidity balance. Incrocci et al.<sup>[151]</sup> proposed that optimal CO<sub>2</sub> concentration in the greenhouse can be based on an economic evaluation. To maintain a given CO<sub>2</sub> concentration within the greenhouse, the supply must balance the assimilated CO<sub>2</sub> flux to the outside air due to **ventilation**. Linker et al.<sup>[152]</sup> optimized greenhouse operation and in particular CO<sub>2</sub> control, using a neural network. Most of these approaches have used crop models and prices of the harvested product. van Beveren et al.<sup>[153]</sup> expanded this process further by including a dynamic CO<sub>2</sub> balance. They reported a method to minimize the total energy that is required to heat and cool a greenhouse. Their research provides a model to define bounds for temperature, humidity, CO<sub>2</sub> concentration, the maximum amount of CO<sub>2</sub> available, and the effect of different bounds on optimal energy input. The addition of the dynamic CO<sub>2</sub> balance provides a truly integrated approach that takes all major aspects of greenhouse climate control into account. This is important, given the trade-off between natural ventilation and the injection of industrial CO<sub>2</sub>, which occurs in a greenhouse with active cooling. Nadal et al.<sup>[154]</sup> presented an energy and environmental assessment for a roof-top greenhouse and showed that their greenhouse achieved an annual saving in CO<sub>2</sub> emissions of 113.8 kg/m<sup>2</sup> per year, relative to an equivalent oil-heated greenhouse. Vadiie and Martin<sup>[155]</sup> developed a theoretical model using TRNSYS to carry out greenhouse energy analysis. From the economic feasibility assessment, their results showed that the concept has the potential of becoming cost effective. A literature survey on greenhouse energy analysis<sup>[156]</sup> has concluded that evapotranspiration has a significant impact on the micro-climate<sup>[156,157]</sup>. This is true since the amount of moisture that is added to the greenhouse environment due to evapotranspiration helps moderate the vapor pressure deficit.

Current advances in CEA systems tend towards sustainability and utilizing renewable energy by studying wind power, solar thermal applications<sup>[142]</sup> and solar energy conservation<sup>[141]</sup> to reduce fuel consumption<sup>[158]</sup>. For example, in tropical and subtropical conditions, the strategy in microclimate control is to improve resource efficiency by benefiting from the potentials of natural ventilation and shading<sup>[120]</sup>. In fact, studies of different control strategies indicated that smart management of natural ventilation for manipulating the environment under specific exterior conditions is an effective approach to improve productivity and increase benefits<sup>[124]</sup>. A smart tropical greenhouse that operates on solar panels and benefits from an adaptive design and covering materials (i.e., mesh screens) will maximize the use of natural and mechanical ventilation<sup>[144, 159-162]</sup> and will be less dependent on higher-cost cooling methods such as evaporative<sup>[67,163-167]</sup> and high pressure fogging systems<sup>[168]</sup>. Nevertheless, the use of anti-insect screens decreases the natural ventilation capacity and aggravates thermal conditions. It is therefore unrealistic to completely eliminate other means of cooling,

especially during peak hours of cooling requirement. Compared to the wet pad-and-fans, fogging systems have shown to be more suitable under such climate condition<sup>[165]</sup>. A comprehensive review of advances in greenhouse microclimate control and automation system for tropical regions is available in [169].

### 4.3 Environment prediction and yield estimation models

Greenhouse growers use prediction tools for the weather forecast, photosynthesis predictions for plant growth progress<sup>[170]</sup>, predicting disease<sup>[171]</sup>, simulation of yield<sup>[172]</sup>, and production planning and cost-benefit analysis. Some of the earlier examples of climate models to predict the temperature and humidity inside a greenhouse can be found in the works of [7, 173-176]. A thermal model for prediction of microclimate factors inside a greenhouse with mechanical ventilation and an evaporative cooling system was introduced by Willits<sup>[75]</sup>. More recent mathematical models for predicting greenhouse microclimate from external data have been addressed in [121, 177-180]. An innovative air temperature prediction model based on least squares and support vector machine with optimized parameters using an improved particle swarm optimization (IPSO) technique is presented in [181]. The authors compared and validated the performance of their model with conventional modeling techniques by predicting the air temperature in a solar greenhouse. Another example is KASPRO, an advanced dynamic model for microclimate prediction in greenhouses<sup>[176,182]</sup>. This model consists of sub-functions based on mass and energy balance of the greenhouse environment. A detailed description of this model is presented in the work of Rigakis et al.<sup>[78]</sup> This model was used by Graamans et al.<sup>[183]</sup> to describe crop transpiration and energy balance in plant factories by determining vapor flux and the relation between latent and sensible heat exchange for production of lettuce.

Sustainable development of modern greenhouse production systems also requires yield estimation models and knowledge-based information software for adaptive management of resources. Since it is impossible to actually plant and experiment with every single greenhouse design and climate scenario, mathematical models for simulation of yields and growth responses are essential for achieving high yield at low cost. These models can also contribute to the optimization and management of greenhouse energy under adverse climate conditions. An early example includes the work of Gary et al.<sup>[184]</sup> in which an educational software called SIMULSERRE for simulating greenhouse plant system was developed. Some of the well-known simulation models for tomato plants include TOMSIM<sup>[185]</sup>, TOMPOUSSE<sup>[186,187]</sup> and TOMGRO<sup>[188,189]</sup>. A common weakness with these models is that their parameters are specific for the climate condition and greenhouse design that they were derived from. In addition, because of the complexity of the interactions between the greenhouse elements and the crop itself, it is often impossible to correctly predict microclimate effects on the final yield with the same model parameters. One of the most widely accepted yield simulation models is the TOMGRO<sup>[189]</sup> in which the author claimed that “it is possible to use the same reduced model with parameters estimated at one location to simulate leaf area and above-ground weight of tomato growing in greenhouse conditions in other locations”. The first version of TOMGRO<sup>[188]</sup> and the third version<sup>[190]</sup>, respectively had 69 and 574 state variables for simulation of tomato growth on

the basis of three inputs that are measured inside greenhouse environment: the photosynthetically active radiation,  $\text{mmol}/(\text{m}^2 \text{ s})$ , air temperature,  $^{\circ}\text{C}$  and  $\text{CO}_2$  concentration, ppm. A simplified version of TOMGRO<sup>[189]</sup> was developed with the objective of providing a practical application and only has five steady-state variables: (i) node number for the main stem, (ii) leaf area index, (iii) total plant dry weight ( $W_T$ ), (iv) total fruit dry weight ( $W_F$ ), and (v) mature fruit dry weight ( $W_M$ ). Jones et al.<sup>[189]</sup> provided simulation results for three tomato varieties including DeRuiters, Beefsteak, and Bigboy respectively for three experiment locations at Gainesville (Florida), Avignon (France) and Lake City (Florida). Some of the studies related to evaluation and adaptation of TOMGRO model to specific climate conditions and cultural practices can be found in the works of [172, 191, 192]. It should be noted that the simplified TOMGRO model only takes into account the effect of air temperature and light condition, and other important variables such as  $\text{CO}_2$  concentration were not included in this version. In addition, Jones et al.<sup>[189]</sup> did not take the work any farther than making the model calculations in an Excel spreadsheet, hence the model could not be used directly with other models to control greenhouse environments. To fill this gap, Shamshiri et al.<sup>[193]</sup> evaluated and verified the performance of the reduced state variable version of TOMGRO model of Jones et al.<sup>[189]</sup> using boundary data that were expected to result in zero yield output. The hypothesis was to test whether the model parameters are robust enough to translate an adverse greenhouse environment (with air temperature so high to prevent any crop growth development) to realistic biomass and yield. For this purpose, Shamshiri et al.<sup>[193]</sup> converted the model from spreadsheets format to Matlab Simulink (The MathWorks Inc, Natick, MA, USA), provided a user interface to access the TOMGRO inputs and outputs, and replaced the lengthy calculation procedures of Microsoft Excel with one-click step operation in Matlab. This Simulink model of Shamshiri et al.<sup>[193]</sup> provided a flexible platform for individuals unfamiliar with computer programming languages and crop modeling to have an easy access to the TOMGRO model functionality. It was shown that the designed Simulink model can be used reliably as a replacement for the spreadsheet version of TOMGRO model. Additional research works with experimental and simulated based studies for investigating the effects of structure design, covering materials and control systems on greenhouse microclimate, crop transpiration, and expected yields are available in the works of [51, 55, 76, 120, 193, 194].

### 4.4 Decision support systems

The management of production in a greenhouse requires decision making on several tasks and time scales. These decisions are mainly related to management of the crop growth conditions<sup>[195]</sup>, the culture period and practice such as seedling production<sup>[196]</sup>, event-based irrigation<sup>[197]</sup> and the control and management of environment based growth models<sup>[198]</sup>. Research and development in decision support system (DSS) for greenhouse application began during the 1990s, primarily for recommending microclimate reference values and set-points, and for pest and disease management. Early studies included the works of Fisher et al.<sup>[199]</sup>, Clarke et al.<sup>[195]</sup> and Sun et al.<sup>[200]</sup>. A DSS was built by Tchamitchian et al.<sup>[201]</sup> based on the

mathematical formalization of expert practices and scientific knowledge to generate set-point values for greenhouse cultivation of tomato is reported to contribute to energy saving of 5%-20%. A similar application is presented in [202] for decision making about the climate control regime that can quantify the energy costs based on different control strategies. More recent studies can be found in the works of Cañadas et al.<sup>[203]</sup> and Aiello et al.<sup>[204]</sup>

An interactive decision support system (DSS) developed by Short et al.<sup>[205]</sup> based on the HYTODMOD growth response model of El-Attal<sup>[206]</sup> is available to describe the optimality degrees of air temperature and relative humidity at five growth stages and under three light conditions (night, sun and cloud). These functions were tested and validated by four independent expert growers and were results of experiments with tomato cultivar “Caruso” in an A-Shade greenhouse located at the Ohio Agriculture Research and Development Center with a floor area of 7.3 m<sup>2</sup>. In order to build a model for defining the optimality degrees of VPD at different light conditions and growth stages of tomato, Shamshiri et al.<sup>[207]</sup> integrated the growth response model of El-Attal<sup>[206]</sup> and developed the OptVPD model (Figure 6) with a series of membership function that take VPD (kPa) as input, and generate a real number between 0 and 1 as output. The effects of air temperature ( $T$ ) and relative humidity ( $RH$ ) on the optimality degree of VPD based on this model are shown in Figure 6. The knowledge behind these functions and the optimal and failure microclimate values were condensed from extensive peer-reviewed scientific published research on greenhouse cultivation of tomato and physiology, with the goal of

simultaneously achieving high yield and high-quality fruit. Shamshiri et al.<sup>[120]</sup> extended and implemented TOMGRO model in SIMULINK and interfaced it with the HYTODMOD and OptVPD for microclimate evaluation and yield estimation (Figure 7). The interfaced HYTODMOD, OptVPD, and TOMGRO models can be used as a DSS tool for evaluation purpose by exploring optimality degrees of the microclimate and macroclimate parameters as well as yield estimation depending on the growth stage of the plant and different light condition. It allows growers to manually change the values of the growing parameters as well as the growth stages and receive a feedback by means of a number between 0 and 1 representing how close that parameter is to high yield and high quality. An application of this DSS has been presented for dynamic assessment<sup>[208]</sup>, measuring optimality degrees<sup>[46]</sup>, and comparative evaluation of microclimate parameters<sup>[193]</sup> in greenhouses with different covering materials. Microclimate evaluation with VPD influences the energy costs involved in greenhouse cultivation and must be taken into account in humidity and temperature control algorithms. A more in-depth analysis and practical examples of this DSS is presented by Shamshiri et al.<sup>[120]</sup> via an adaptive management framework. This framework provides a flexible platform for altering each participating variables in the greenhouse. It simulates growth and environment responses in different light condition, growth stages, growing season and location. The result is a cost-benefit analysis that shows at what level each combination of variables is close to the optimal requirements.

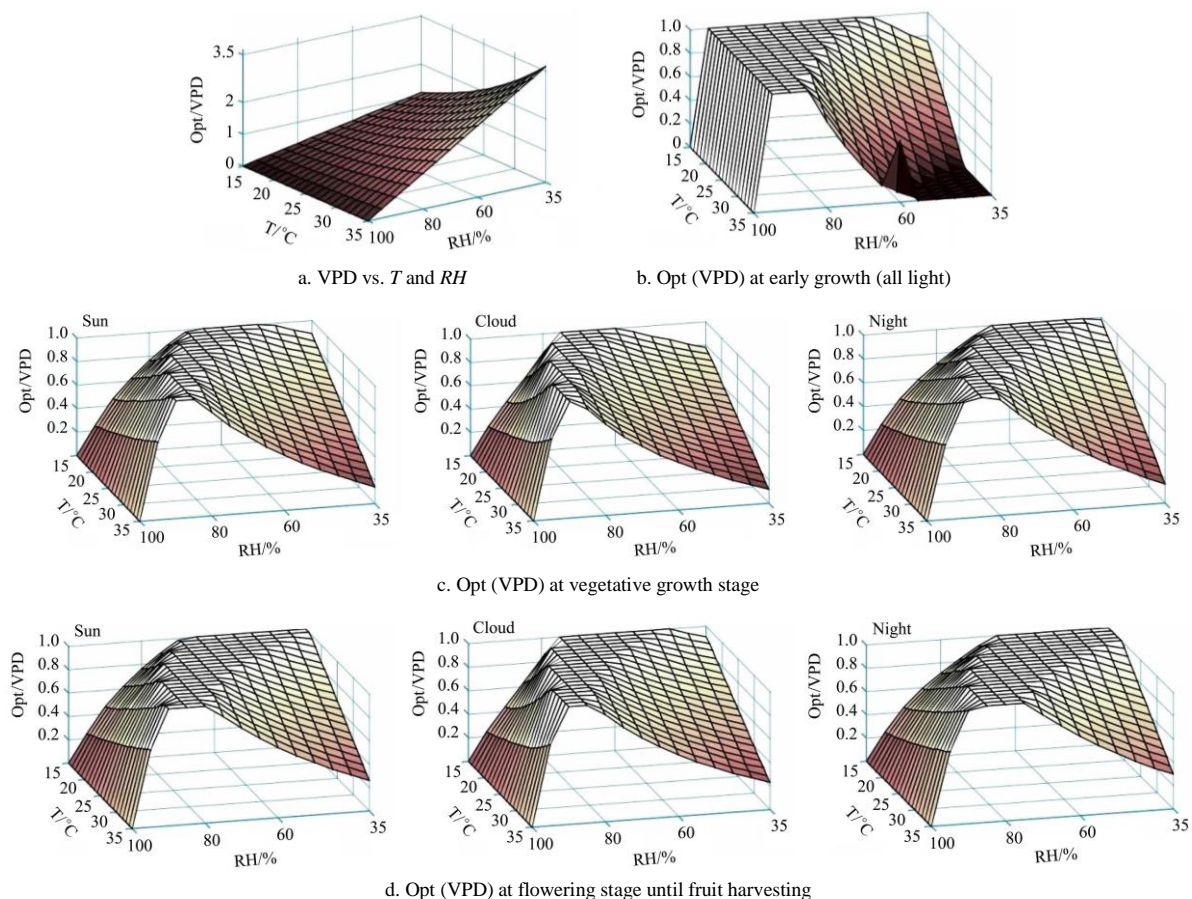


Figure 6 Variation in VPD with respect to  $T$  and  $RH$  (a) and effect of  $T$  and  $RH$  on the optimality degrees of VPD at different light conditions and growth stages in greenhouse tomato cultivation (b-d)



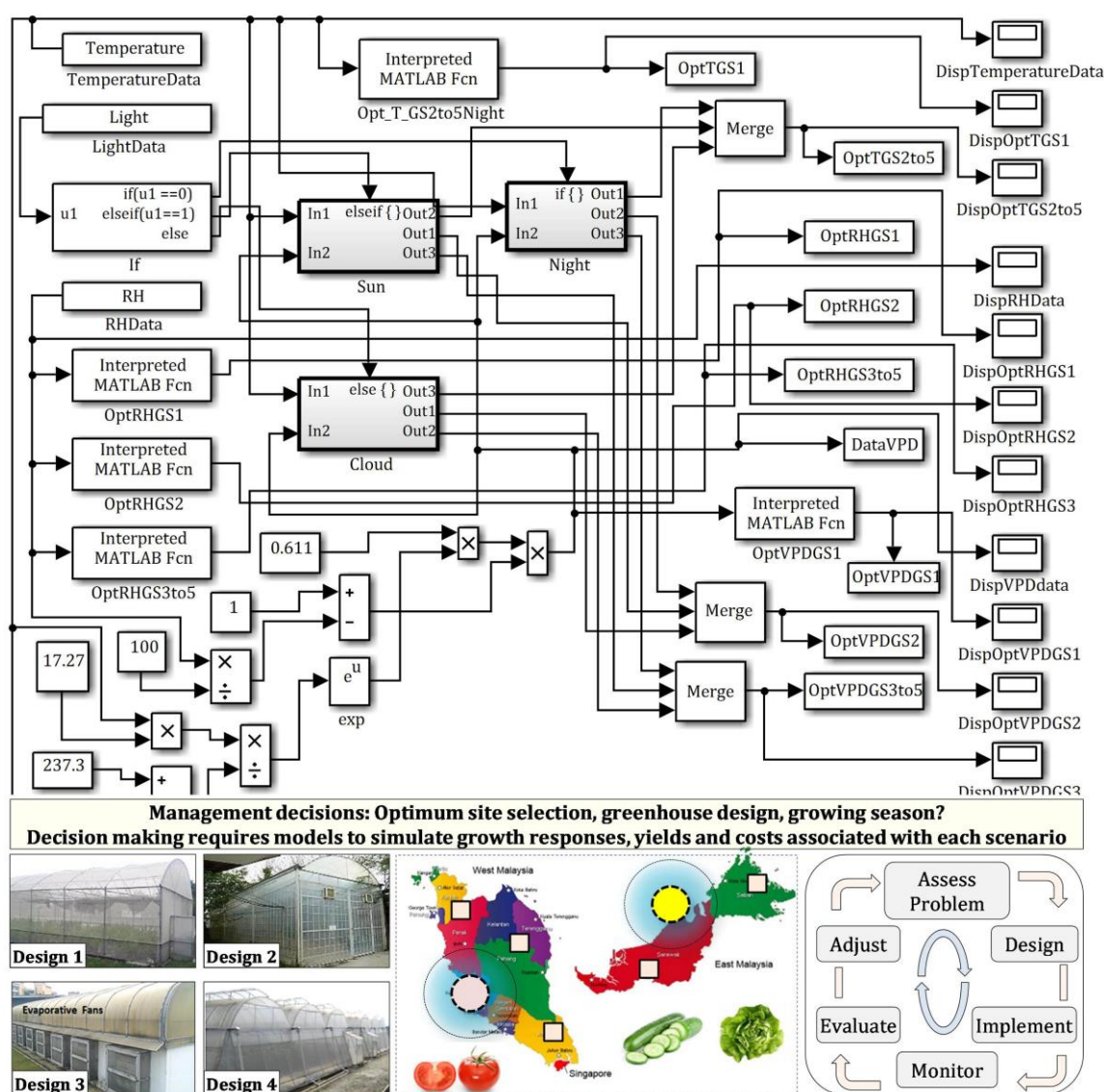


Figure 7 Snapshot of the OptVPD sub-model, a part of the DSS based on adaptive management framework architecture for maximizing tomato yield<sup>[120]</sup>

## 5 Urban agriculture (UA)

The fast growth of global population is changing the food production systems to keep up with the growing demands. Agricultural innovation and research in the past three decades, combined with the advances in information technology have introduced promising cultivation techniques that are valuable for sustainability and economic viability of CEA. Ellis<sup>[209]</sup> described that throughout the history, agriculture has always been associated with urban centers, much more than it is imagined today. While traditional and modern agriculture have been separated in the upper layers, they are still attached to each other in the roots. Today, food, as well as animal livestock, is surrounding us everywhere, and the question about the origin of this supply is not a concern anymore. By the late 2000s, major cities reached the point that most people did not even need to associate food with natural resources<sup>[210]</sup>.

The concepts in UA and the associated facilities have received significant attention and popularity in the last 8 years, and are growing to meet the needs of the ever-developing urban life. A variety of systems may fall under UA concept in different scale and possession (Figure 8), ranging from a personal

or local community gardens for social and self-sufficiency purposes, to complicated systems which involve indoor food production with the help of artificial light or inside factories that are capable of controlling the climate to produce sensitive plants. Since UA is mostly practiced indoors, it is also referred as vertical farming (VF)<sup>[211]</sup>, integrated farming inside buildings<sup>[212]</sup>, and Z-farming (which stands for ZeroAcreageFarming)<sup>[213]</sup>. This type of food production is entering all cities in the world and has attracted public interest. There are new consumers' needs for fresh food of good quality with no damage to nature. Several reports indicated that more projects are involved in bringing farming products into cities<sup>[214,215]</sup>. "UA is an industry that makes, processes and markets food and fuel, mostly in reaction to the daily need for consumers in a town, city, or metropolitan areas, on land and on water spread in the urban and semi-urban area, by employing many methods of production, using and recycling natural resources and city wastes to produce a variety of products and livestock"<sup>[216-219]</sup>. In fact, UA is a farming movement in the cities for circulation of food and non-food plants and tree products. Some of the suggested solutions for a closed-field production system in UA are the plant factories, vertical farming (VA), and rooftop greenhouses.





Source: <http://urbanizehub.com>.

a. Conceptual demonstration of urban agriculture inside the high-density areas of transforming cities



Source: <https://weburbanist.com> a city center.

b. Conceptual design of a smart urban farm inside a city center

Figure 8 Conceptual demonstration of urban agriculture inside the high-density areas of transforming cities and conceptual design of a smart urban farm inside a city center

### 5.1 Vertical farming and rooftop greenhouses

The concept of VF is not new. Kaplan<sup>[220]</sup> explained that VF has been unknown for a long time, and was then brought to attention in the recent years through the advances in technology. Life magazine has published one of the very first sketches of a tall construction that promotes agricultural products for people daily food requests as early as 1909. In 1915, the American geologist Gilbert Ellis Bailey used the concept of the tall multi-story buildings for indoor cultivation. He created the term “Vertical Farming” in his book with the same title as “Vertical Farming”<sup>[221]</sup>. Designers and landscape architects have frequently looked into the concept, particularly at the end of the 20<sup>th</sup> century. During the 1970s until the early 1980s, the Malaysian-born architect, Ken Yeang improved and advanced the ideas of Bailey into an architectural project<sup>[222,223]</sup>. It is called Bioclimatic Skyscraper (Menara Mesiniaga) that was built in 1992. In 1993, Nancy Jack Todd and John Todd envisioned the idea of VF in their book entitled “From Eco-Cities to Living Machines”. The most recent and greatest challenging form of this idea however appeared in 1999 by Dickson Despommier’s, an Emeritus Professor of Microbiology at the Columbia University, speculating that a 30-floor farm on one city block could provide food for 50 000 people with vegetables, fruit, eggs and meat, explaining that hydroponic crops could be grown on upper floors; and the lower floors would be suited for chickens and fish that eat plants waste. In the concept of VF, heat and lighting would be provided by geothermal, tidal, solar, or other recyclable sources of energy. Nitrogen along with other nutrients would be sieved from animal waste and maybe from the urban sewage system. It should be noted that until 2010, there was no report of evidence for VF

construction before it began emerging in USA, Singapore, Japan, and Korea. In theory, VF is the technique that includes large-scale food production in skyscrapers that makes rapid growth and planned production possible through managing nutrient solution of crop and the growth context according to hydroponics methods. With the help of cutting-edge greenhouse approaches, these buildings can be used as a precision farming system that paves the way for the acquisition of a safe crop growth through controlling and supervising of the microenvironment using sensors, interfacing gadgets and instrumentation<sup>[210,213,224-227]</sup>.

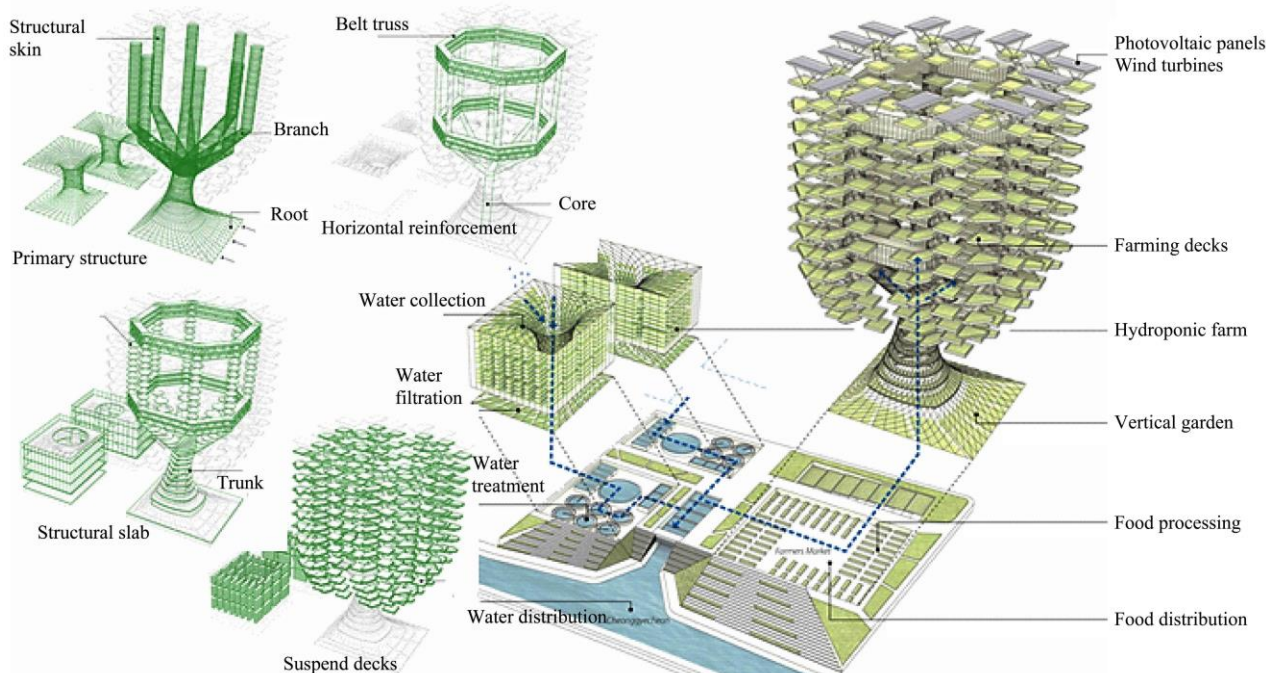
In the recent years, the majority of scientific publications in UA have focused on different aspects of the VF concept. For example, Sivamani et al.<sup>[228]</sup> studied the viability of smart technology used in agriculture as an opportunity to be used for VF<sup>[228,229]</sup>. Research findings have shown that VF is a promising technique for providing food for cities in a sustainable way. However, it is also a function of the location and design<sup>[229]</sup>. It is mentioned that VF is a way of feeding and at the same time a movement in the society to reduce greenhouse gas emission<sup>[219,230]</sup>. A common debate about VF is the compromising between the building structure and the returns. Some estimates that an abandoned building can be adapted to the needs of VA, while other believes that only buildings with new design will satisfy that need. A study by Kalantari et al.<sup>[231]</sup> presented several effective VF projects in different countries by estimating their feasibility and viability in various geographical areas. The data was shaped based on the technology of different VF in different climate areas. It was shown by Kalantari et al.<sup>[231]</sup> that every VF has its own technologies and techniques according to the different geographical locations. Table 1 presents the details of some of effective VF projects in different countries and shows the different areas by their type of building and typologies. An interesting example includes the conceptual design of the Urban Sky-farm for downtown of Seoul is shown in Figure 9 with different sections of the structure illustrated by labels. This design was the winner of the 2013 green dot design competition. The key concept of a vertical farm is to yield as much crop as possible under optimal circumstances, even in the center of cities. Thus, the VF shown in Figure 9 includes many floors with a variety of crops on each. Different crops need different environmental conditions. Therefore, tracing a crop and its location is of a great significance<sup>[228]</sup>.

Vertical farms can be diverse from city to city and their structures also vary around the world<sup>[210]</sup>. The other two conceptual designs for vertical farms are shown in Figure 10. The first design (Figure 10a) was designed by ODESIGN group for Australia. The other type of VF called urban farming units (UFU) is shown in Figure 10b, a farm within shipping containers that can produce organic fish, fruits, and vegetables in the street. The entire prototypes are rooted in circular agriculture techniques. The main goals of UFU are to find a way to grow food under polluted and limited ground<sup>[232]</sup>. Figure 10b shows a conceptual design of an Aquaponics farm with fish tanks that can be placed inside or close to the plant in different levels of the farm. In this system, the plants clean and purify the water for the fish, and in return, fish feed the plants with their waste as a source of nutrients. The Freight Farms in Table 1 is also an example of a vertical farm in a shipping container.

Another solution for UA is the rooftop greenhouse (RTG) and building integrated rooftop greenhouse (i-RTG) concept. It is defined as a greenhouse constructed on top of a building, usually matched with soilless culture systems<sup>[233]</sup>. Several advantages of

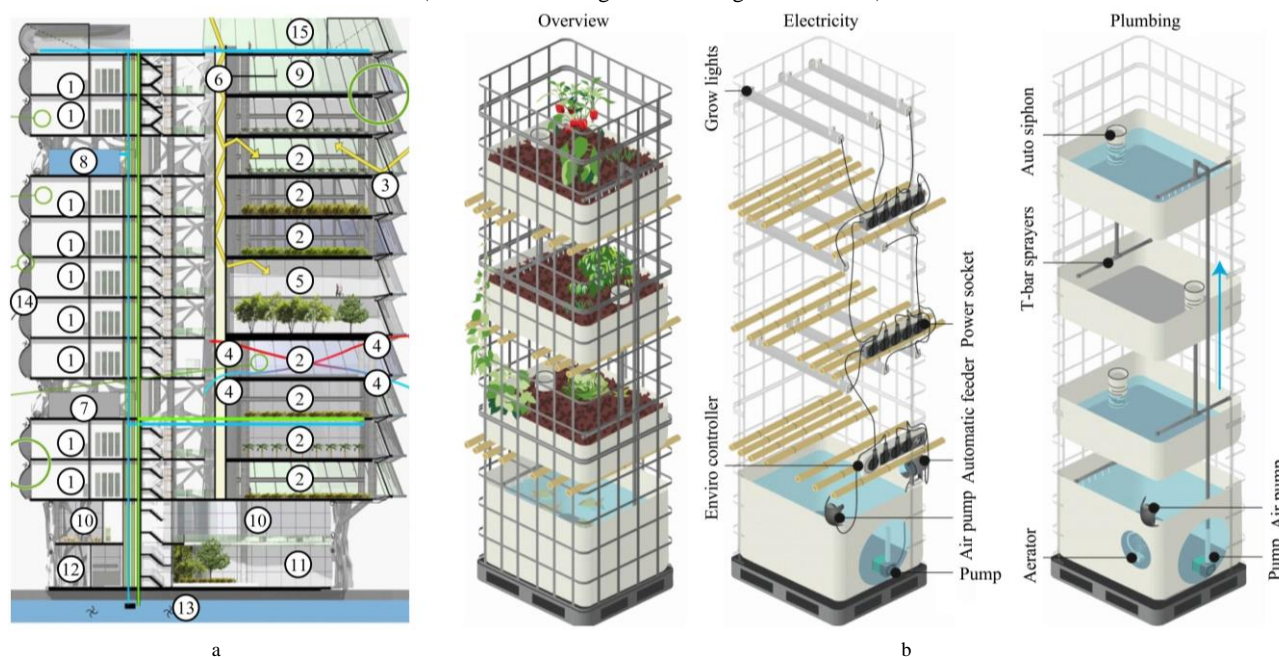
these structure have been reviewed by Pons et al.<sup>[234]</sup> and Sanyé-Mengual et al.<sup>[235]</sup>, and were classified as the quality parameters for the greenhouse and building (i.e., energy saving), global advantages (as the effect on climate change decrease), local advantages (such as naturalization of urban areas), integrations and adaptations with the building, as well as production benefits (including the accessibility of high quality food). These structures can optimize the energy, water, and CO<sub>2</sub> flows only when the RTG and the building are capable of exchanging air and can harvest the rainwater or make use of the decently treated grey water for the purpose of irrigation. Some experimental research indicated that

i-RTG has failed to provide proper light transmission<sup>[236]</sup>, resulting in low radiation use efficiency (RUE), however this issue is not concerning RTG structure. In comparison to traditional greenhouses in the region, which are generally unheated, a primary advantage of i-RTG is their better and more uniform temperature regime, owing to the thermal links to the building. This is an obvious benefit for energy saving over the conventional ground greenhouses. Some of the examples of RTG farming companies include VertiCrop TM, Gotham Greens, Bright Farms and Lufa Farm, with details available in Table 1. It was unable to find published reports for a successful commercial scale example of i-RTG.



Source: adapted from <http://www.aprilli.com/urban-skyfarm/>.

Figure 9 Conceptual design of the urban sky-farm, a vertical farm design proposal for a site located in downtown Seoul (the winner of the green dot design award 2013)



1. Hydroponic and Aquaponics 2. Location for crop selection 3. Reflective edge or light shelf 4. Multiple ventilation scenarios 5. Orchard section 6. Light tube
7. Plant level, location is flexible 8. Water storage level 9-10. Restaurant and café 11. Entry 12. Storage 13. Water turbines 14. Wind turbines 15. Rooftop farming.

Source: <https://www.mediamatic.net>.

Figure 10 Conceptual layout design of a vertical Aquaponics farm



**Table 1 Details of effective vertical farming around the world (Adopted from Kalantari et al.<sup>[231]</sup>)**

Company name	Location	Area	Typology of VF	Type of Building	Growing plants	Year	Company website
The Plant Vertical Farm	Chicago, IL	100 000 ft <sup>2</sup>	Multi-story with Stacked Bed design	NC	Artisanal brewery, kombucha brewery, mushroom, and bakery Tilapia as an aquaculture product	2013	plantchicago.com
Sky Green Farms	Singapore	600 m	One floor (9 m) by rotating tiers on an A-shape aluminum frame	NC	Leafy green vegetables like Radishes, spinach	2009	skygreens.appsfly.com
VertiCrop TM	Vancouver, Canada	3750 ft <sup>2</sup>	One floor with Columnar design	RTCB	Strawberries with Leafy greens and micro greens	2009	verticrop.com
Republic of South Korea VF	South Korea	450 m <sup>2</sup>	3 multi-story with Stacked Bed design	NC	Leafy green vegetables with corn and wheat	2011	cityfarmer.info
Gotham Greens	Brooklyn, USA	1400 m <sup>2</sup>	One floor with Stacked Bed design	RTCB	Lettuce, Asian Blend, Tropicana Green Leaf, Red Oak Leaf, etc.	2011	gothamgreens.com
Mirai Company	Japan	25 000 m <sup>2</sup>	One floor with Stacked Bed design	NC	Lettuce	2015	miraigroup.jp
Nuvege plant factory	Japan (Kyoto)	30 000 ft <sup>2</sup>	4 multi-floor with Stacked Bed design	NC	Leafy green vegetables		nuvege.com
PlanetLab VF	Den Bosch, Holland		3 multi-floor with Stacked Bed design	UEB	Beans, corn, cucumbers, tomatoes, and strawberries	2011	plantlab.nl
Vertical Harvest plans2	Jackson Wyoming, USA	4500 ft <sup>2</sup>	3 multi-floor with Stacked Bed design	NC	Tomatoes, strawberries, lettuce, and micro greens	2012	verticalharvestjackson.com
Planned Vertical Farm	Linköping, Sweden	-	17 multi-floor	NC	Asian leafy green vegetables	2012	plantagon.com
Green Sense Farms	Portage, Indiana Shenzhen, China	20 000 ft <sup>2</sup>	Stacked Bed design	NC	Micro Greens, Baby Greens, Herbs, Lettuces	2014 2016	greensensefarms.com
Aero Farms	Newark, New Jersey	20 000 ft <sup>2</sup>	Stacked Bed design	NC	250 different types of leafy greens and herbs like mizuna, kale, and arugula	2012	aerofarms.com
Bright farms	Bright farms	0.405 hm <sup>2</sup>	One floor with Stacked Bed design	RTCB	Tomatoes, lettuce, Spinach, Spinach, Arugula and Kale		brightfarms.com
Lufa Farms Lavel Ahuntsic	Montreal, Canada	43 000 ft <sup>2</sup> 32 000 ft <sup>2</sup>	One floor with Stacked Bed design	NC RTCB	Tomato, cucumber, pepper, etc	2013 2011	montreal.lufa.com
Thanet Earth Farm	Kent, Britain	-	One floor with Stacked Bed design	GnF	Tomatoes, peppers, cucumbers		thanetearth.com
Freight Farms	Boston, USA	40 ft <sup>2</sup>	One floor with Stacked Bed design	SC	Lettuces, herbs, and hearty greens	2010	freightfarms.com

Note: NC: New construction; RTCB: Rooftops of commercial building; SC: Shipping container; GnF: Ground floor; UEB: Underground of existing building.

## 5.2 Plant factories

Plant factories are usually used for commercial production of leafy greens, but their potential remains uncertain. A general structure design of a plant factory and corresponding components sections are shown in Figure 11. In order to achieve economic viability, the increased resource productivity and/or the value of additional services in these structures would have to outweigh the disadvantage of the absence of solar energy. Plant factories have been primarily used in Asia to refer to a commercial plant production factory similar in operations to an ordinary industrial firm. Some of the technological instrumentations and equipment supporting these factories for deriving the plants to their maximum potentials are precision sensors, nutrition solution, process controllers, automated instruments, computer systems, and environmental supervision along with implementation of DSS and task management software. Moreover, a number of plant factories also benefits from robotic systems for sorting, transferring, and handling of the plants, as well as quality control, and post-harvesting. Because of the relatively higher economic investment that is required for plant factories, they are managed with resource efficiency and production predictability to attain market-valuable crops.

In the Japanese context, there existed 165 plant factories which are using artificially lighting combined with natural solar lights<sup>[237]</sup>. Additional sub-system might be required in plant factories for air exchange to eliminate the temperature increase due to the artificial light. Plant factories which have full artificial light sources usually utilize opaque building materials. This would offer a

chance to have the walls and roofs well resistant which makes controlling the internal temperature easier and helps conserve the energy. Furthermore, often the skin facade of the building is covered by a self-cleaning and transparent material such as Ethylene Tetra Fluoro Ethylene (ETFE). In addition, a material which is highly clear and a high thermal rate are required to increase the intensity of sunlight that enters the building. ETFE is light enough as it enjoys only 1% weight of an equal-sized piece of glass. However, it lets in 95% of light. There exists a different intensity of pressure between the ETFE layers. Such a pressure helps to close and open the screens so as to change the passage of sunlight<sup>[209]</sup>. ETFE which is a standardized construction material has been used on an extensive surface of ethereal domes in the Eden Project in the south of England<sup>[14,238]</sup>.

Studies showed that quantitative blue light was able to improve photosynthetic performance or growth through motivating morphological as well as physiological responses. Miyagi et al.<sup>[239]</sup> showed that synergistic effects of monochromatic LED together with high CO<sub>2</sub> and nutrients can enhance lettuce growth in a plant factory. Shimokawa et al.<sup>[240]</sup> concluded that red and blue irradiation used at the same time improve plant growth more than monochromatic and fluorescent light irradiation. These researchers also observed that alternatively use of red and blue light accelerated plant growth dramatically, with the fresh weight of a randomly measured plant that was found to be two times as much as the usual LED production methods. The bacterial biofertilizers used in plant factories may positively affect plant growth in several





and the introduction of new affordable and energy efficient LED lighting is an accepted substitute to compensate the lack of natural light. We mentioned earlier that the LED sources are capable of increasing the yield in greenhouse context significantly because of matching spectral features with plant type and physiology<sup>[229,242]</sup>. In addition, extra sun exposure is also possible through stacked levels of plants that can be rotated within one high-rise closed-space.

The extra cost of VF start-ups can be resolved if the supporting structures are not built on the expensive central business districts, however there are still several challenges with VF. Indeed, the primary costs of establishing, equipping and implementing a VF are certainly high and are mostly accounted for energy consumption. The number and variety of crops grown is not as many as in rural farming. The quantity and loads of the crops are also not as much as in the open-field cultivation. There are other challenges too such as the need for disruption management to the rural sector, to raise investment capital, and to train workforce. These costs will be lowered through the time, particularly those concerning energy provision. Abel<sup>[210]</sup> also mentioned that although establishing VF is very costly at the beginning, but when it is well-established and fully operated, the price of food will be lowered. According to Despommier<sup>[14]</sup>, there are many appropriate locations for VF projects in every city and if these locations are used efficiently, they are able to return and circulate large sums of money to the city<sup>[245]</sup>. It is concluded by Voss<sup>[246]</sup> that assessing all conditions on every level is essential, in order to thoroughly consider all possibilities and then to decide on the establishment of a VF. Furthermore, VF as a concept is a promising move along the right path for the fans of the revolutionary resource-based economy movement. Economic analysis, along with the exploration of the impact of VF on post-industrial cities can be topics of future studies.

## 6 Conclusions

Urbanization and living in multi-story buildings request a redefinition of agricultural awareness for securing food supply. The economic viability of traditional greenhouses in this new scenario is likely to fade in the coming decades. A trend in the past 15 years of published literature showed that researchers and greenhouse growers have become more interested in shifting towards smart controlled environment agriculture. The research concentration has shifted from instrumentation control and hardware-software interfacing to other scopes, such as simulating the interactions between microclimate parameters and plant growth. Researchers in this field are developing complex mathematical models to minimize energy inputs, or are interested in finding innovative solutions for replacing the fossil energy consuming greenhouses with energy neutral CEA systems that operate on solar and wind power. The main aspect that requires improvements in this field is the task planning algorithms. Path planning is well known, but to provide the CEA with an adaptive design and control strategy that forms the right shape and perform the right task at the right time, while increasing profits and remaining competitive in the market is still a challenge. This research presented an overview of modern greenhouses, controlled environment agriculture and their derivatives, and highlighted some of the advances in environmental monitoring, control, and optimization. While biological sensors, like those that measures plant stress are the key to such high-level of automation, this technology is either very expensive for local growers to afford, or even not available. In addition, it is not clearly well known the cost of increased

automation relative to increase in profitability. Therefore, another area helping sustainability is knowledge based and decision making support systems, i.e., model based computer applications that address the cost benefit for a proposed automation technology. This paper highlighted some the most recent technological advances for closed-field agriculture by reviewing the applications of plant factories and rooftop greenhouses. Some of the conceptual designs in this context were introduced along with several existing commercial examples to show the trends in developing sustainable farming system in the center of dense cities. Based on the review literature, this study concludes that a more accurate economic analysis and justifications of the high startup costs involved with vertical farming and plant factories are required before large-scale commercial development. The computer simulation models and adaptive analysis software are already available for greenhouses and CEA systems can be extended and modified for this purpose. The cost of increased automation level relative to increases in profitability is a key consideration, and should form part of future study to justify the implementation of a greater level of automation.

## [References]

- [1] Ting K C, Lin T, Davidson P C. Integrated urban controlled environment agriculture systems. In: Kozai T, Fujiwara K, Runkle E S. Singapore: Springer Singapore, 2016; p. 19–36.
- [2] Muijzenberg E W B. A history of greenhouses. Wageningen: Institute of Agricultural Engineering, 1980; 435 pp.
- [3] Woods M, Warren A S. Glass houses: A history of greenhouses, orangeries and conservatories. Rizzoli, 1988.
- [4] Enoch H Z, Enoch Y. The history and geography of the greenhouse. Ecosystems of the world, 1999; 1–16.
- [5] De Vleeschouwer O. Greenhouses and conservatories. Flammarion, 2001.
- [6] Cuce E, Harjunowibowo D, Cuce P M. Renewable and sustainable energy saving strategies for greenhouse systems: A comprehensive review. Renewable and Sustainable Energy Reviews, 2016; 64: 34–59.
- [7] Takakura T. Development of VETH chart using computer. Technical report on design standards of greenhouse environmental control systems. University of Tokyo, 1976.
- [8] Udink ten Cate A J, Bot G P A, van Dixhoorn J J. Computer control of greenhouse climates. International Society for Horticultural Science (ISHS), Leuven, Belgium, 1978.
- [9] Aitken-Christie J, Kozai T, Smith M A L. Automation and environmental control in plant tissue culture. Springer Science & Business Media, 2013.
- [10] Hanan J J. Greenhouses: Advanced technology for protected horticulture. CRC press, 1997.
- [11] Critten D L, Bailey B J. A review of greenhouse engineering developments during the 1990s. Agricultural and Forest Meteorology, 2002; 112(1): 1–22.
- [12] 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. In: Jurić S. Rijeka: InTech, 2017.
- [13] Nelkin J, Caplow T. Sustainable controlled environment agriculture for urban areas. International Society for Horticultural Science (ISHS), Leuven, Belgium, 2008.
- [14] Despommier D. The vertical farm: controlled environment agriculture carried out in tall buildings would create greater food safety and security for large urban populations. Journal für Verbraucherschutz und Lebensmittelsicherheit, 2011; 6(2): 233–236.
- [15] Kacira M, Sase S, Okushima L. Optimization of vent configuration by evaluating greenhouse and plant canopy ventilation rates under wind-induced ventilation. Transactions of the ASAE, 2004; 47(6): 2059.
- [16] Baudoin W, Nono-Womdim R, Lutaladio N, Hodder A, Castilla N, Leonardi C, et al. Good agricultural practices for greenhouse vegetable crops: Principles for mediterranean climate areas. FAO, 2013.
- [17] Garnaud J C. A survey of the development of plasticulture: Questions to be answered. Plasticulture, 1987; 74: 5–14.

- [18] Waaijenberg D, Sonneveld P J. Greenhouse design for the future with a cladding material combining high insulation capacity with high light transmittance. International Society for Horticultural Science (ISHS), Leuven, Belgium, 2004.
- [19] Nisen A, Coutsse S. Photometric properties of double wall plastics used as covering for greenhouses. International Society for Horticultural Science (ISHS), Leuven, Belgium, 1981.
- [20] Graefe J, Sandmann M. Shortwave radiation transfer through a plant canopy covered by single and double layers of plastic. Agricultural and Forest Meteorology, 2015; 201: 196–208.
- [21] Bunschoten B, Pierik C. Kassenbouw neemt weer iets toe. CBS Webmagazine (Centraal Bureau voor de Statistiek), 2003: 3.
- [22] Pollet I V, Pieters J G. PAR transmittances of dry and condensate covered glass and plastic greenhouse cladding. Agricultural and Forest Meteorology, 2002; 110(4): 285–298.
- [23] Tuller S E, Peterson M J. The solar radiation environment of greenhouse-grown douglas-fir seedlings. Agricultural and Forest Meteorology, 1988; 44(1): 49–65.
- [24] Santamouris M, Mihalakakou G, Balaras C A, Argiriou A, Asimakopoulos D, Vallindras M. Use of buried pipes for energy conservation in cooling of agricultural greenhouses. Solar Energy, 1995; 55(2): 111–124.
- [25] Grimstad S O. Supplementary lighting of early tomatoes after planting out in glass and acrylic greenhouses. Scientia Horticulturae, 1987; 33(3-4): 189–196.
- [26] Alhamdan A M, Al-Helal I M. Mechanical deterioration of polyethylene greenhouses covering under arid conditions. Journal of Materials Processing Technology, 2009; 209(1): 63–69.
- [27] Al-Helal I M, Alhamdan A M. Effect of arid environment on radiative properties of greenhouse polyethylene cover. Solar Energy, 2009; 83(6): 790–798.
- [28] Dehbi A, Bouaza A, Hamou A, Youssef B, Saiter J M. Artificial ageing of tri-layer polyethylene film used as greenhouse cover under the effect of the temperature and the UV-A simultaneously. Materials & Design, 2010; 31(2): 864–869.
- [29] Bibi-Triki N, Bendimerad S, Chermiti A, Mahdjoub T, Draoui B, Abène A. Modeling, characterization and analysis of the dynamic behavior of heat transfers through polyethylene and glass walls of greenhouses. Physics Procedia, 2011; 21: 67–74.
- [30] Zhu S, Deltour J, Wang S. Modeling the thermal characteristics of greenhouse pond systems. Aquacultural Engineering, 1998; 18: 201–217.
- [31] Oreski G, Wallner G M, Lang R W. Ageing characterization of commercial ethylene copolymer greenhouse films by analytical and mechanical methods. Biosystems Engineering, 2009; 103(4): 489–496.
- [32] Janjai S, Intawee P, Kaewkiew J, Sritus C, Khamvongsa V. A large-scale solar greenhouse dryer using polycarbonate cover: Modeling and testing in a tropical environment of Lao People's Democratic Republic. Renewable Energy, 2011; 36(3): 1053–1062.
- [33] Castilla N, Hernandez J. Greenhouse technological packages for high-quality crop production. International Society for Horticultural Science (ISHS), Leuven, Belgium, 2007.
- [34] Cabrera F J, Baille A, López J C, González-Real M M, Pérez-Parra J. Effects of cover diffusive properties on the components of greenhouse solar radiation. Biosystems Engineering, 2009; 103(3): 344–356.
- [35] Pollet I V, Pieters J G, Deltour J, Verschoore R. Diffusion of radiation transmitted through dry and condensate covered transmitting materials. Solar Energy Materials and Solar Cells, 2005; 86(2): 177–196.
- [36] Arcidiacono C, D'Emilio A, Mazzarella R, Leonardi C. Covering materials to improve greenhouse microclimate during summer in hot climates. International Society for Horticultural Science (ISHS), Leuven, Belgium, 2006.
- [37] Hemming S, Mohammadkhani V, Dueck T. Diffuse greenhouse covering materials - material technology, measurements and evaluation of optical properties. Acta Horticulturae, 2008; 797: 469–475.
- [38] Jarquín-Enríquez L, Mercado-Silva E M, Maldonado J L, Lopez-Baltazar J. Lycopene content and color index of tomatoes are affected by the greenhouse cover. Scientia Horticulturae, 2013; 155: 43–48.
- [39] Shamshiri R, Ismail W I W, Ahmad D. Experimental evaluation of air temperature, relative humidity and vapor pressure deficit in tropical lowland plant production environments. Advances in Environmental Biology, 2014; 8(22): 5–13.
- [40] Al-Mahdouri A, Baneshi M, Gonome H, Okajima J, Maruyama S. Evaluation of optical properties and thermal performances of different greenhouse covering materials. Solar Energy, 2013; 96: 21–32.
- [41] Kempkes F, Stanghellini C, Hemming S, Dai J. Cover materials excluding near infrared radiation: effect on greenhouse climate and plant processes. International Society for Horticultural Science (ISHS), Leuven, Belgium, 2008.
- [42] Álvarez A J, Oliva R M, Valera D L. Software for the geometric characterisation of insect-proof screens. Computers and Electronics in Agriculture, 2012; 82: 134–144.
- [43] Mrema G C, Gumbe L O, Chepete H J, Agullo J O. Rural structures in the tropics: design and development. Food and Agriculture Organization of the United Nations, 2012.
- [44] Glenn E P, Cardran P, Thompson T L. Seasonal effects of shading on growth of greenhouse lettuce and spinach. Scientia Horticulturae, 1984; 24(3): 231–239.
- [45] Hassanien R H E, Li M. Influences of greenhouse-integrated semi-transparent photovoltaics on microclimate and lettuce growth. Int J Agric & Biol Eng, 2017; 10(6): 11–22.
- [46] Shamshiri R. Measuring optimality degrees of microclimate parameters in protected cultivation of tomato under tropical climate condition. Measurement, 2017; 106: 236–244.
- [47] Lorenzo P, Sánchez-Guerrero M C, Medrano E, García M L, Caparrós I, Giménez M. External greenhouse mobile shading: effect on microclimate, water use efficiency and yield of a tomato crop grown under different salinity levels of the nutrient solution. International Society for Horticultural Science (ISHS), Leuven, Belgium, 2003.
- [48] Teitel M, Zhao Y. Temperature gradients in fan-ventilated greenhouses. International Society for Horticultural Science (ISHS), Leuven, Belgium, 2014.
- [49] Seginer I, Teitel M. Effect of ceiling height on the natural ventilation of an 'infinite' screenhouse: Model predictions. International Society for Horticultural Science (ISHS), Leuven, Belgium, 2014.
- [50] Cockshull K E, Graves C J, Cave C R J. The influence of shading on yield of glasshouse tomatoes. Journal of Horticultural Science, 1992; 67(1): 11–24.
- [51] Qiu R, Song J, Du T, Kang S, Tong L, Chen R, et al. Response of evapotranspiration and yield to planting density of solar greenhouse grown tomato in northwest China. Agricultural Water Management, 2013; 130: 44–51.
- [52] Agele S O, Iremiren G O, Ojienyi S O. Effects of plant density and mulching on the performance of late-season tomato (*Lycopersicon esculentum*) in southern Nigeria. The Journal of Agricultural Science, 1999; 133(4): 397–402.
- [53] Amundson S K. Cultural techniques to improve yield and cost efficiency of greenhouse grown tomatoes. Master theses, The university of Tennessee, 2012: 82.
- [54] Kirimi J K, Itulya F M, Mwaja V N. Effects of nitrogen and spacing on fruit yield of tomato. African Journal of Horticultural Science, 2011: 5.
- [55] Ilić Z S, Milenković L, Stanojević L, Cvetković D, Fallik E. Effects of the modification of light intensity by color shade nets on yield and quality of tomato fruits. Scientia Horticulturae, 2012; 139: 90–95.
- [56] El-Aidy F, El-Afry M. Influence of shade on growth and yield of tomatoes cultivated during the summer season in Egypt. Plasticulture, 1983; 47(3): 2–6.
- [57] El-Gizawy A M, Abdallah M M F, Gomaa H M, Mohamed S S. Effect of different shading levels on tomato plants. 2. yield and fruit quality. International Society for Horticultural Science (ISHS), Leuven, Belgium, 1993.
- [58] Hochmuth G J, Hochmuth R C. Nutrient solution formulation for hydroponic (perlite, rockwool, NFT) tomatoes in Florida. HS796 Univ Fla Coop Ext Serv, Gainesville, 2001.
- [59] Cherie E. The complete guide to growing tomatoes: A complete step-by-step guide including heirloom tomatoes (back-to-basics gardening). Atlantic Publishing Group Inc. Ocala, Florida, 2010.
- [60] Jones J B. Instructions for growing tomatoes in the garden and green-house. GroSystems, Anderson, SC, USA, 2013.
- [61] Morison J I L, Morecroft M. Plant growth and climate change. John Wiley & Sons, 2006: 209 p.
- [62] Zhang Z, Gates R S, Zou Z R, Hu X H. Evaluation of ventilation performance and energy efficiency of greenhouse fans. Int J Agric & Biol Eng, 2015; 8(1): 103–110.
- [63] Arbel A, Barak M, Shklyar A. Combination of forced ventilation and fogging systems for cooling greenhouses. Biosystems Engineering,

- 2003; 84(1): 45–55.
- [64] Sabeh N C, Giacomelli G A, Kubota C. Water use for pad and fan evaporative cooling of a greenhouse in a semi-arid climate. International Society for Horticultural Science (ISHS), Leuven, Belgium, 2006.
- [65] Gázquez J C, López J C, Pérez-Parra J J, Baeza E J, Saéz M, Parra A. Greenhouse cooling strategies for mediterranean climate areas. International Society for Horticultural Science (ISHS), Leuven, Belgium, 2008.
- [66] Gázquez J C, Lopez J C, Baeza E, Saez M, Sanchez-Guerrero M C, Medrano E, et al. Yield response of a sweet pepper crop to different methods of greenhouse cooling. International Society for Horticultural Science (ISHS), Leuven, Belgium, 2006.
- [67] Duan Z, Zhan C, Zhang X, Mustafa M, Zhao X, Alimohammadisagvand B, et al. Indirect evaporative cooling: Past, present and future potentials. Renewable and Sustainable Energy Reviews, 2012; 16(9): 6823–6850.
- [68] Schnelle M A, Dole J M. Greenhouse structures and coverings. Division of Agricultural Sciences and Natural Resources, Oklahoma State University, 2015:1–4.
- [69] Li S, Willits D H. Comparing low-pressure and high-pressure fogging systems in naturally ventilated greenhouses. Biosystems Engineering, 2008; 101(1): 69–77.
- [70] Abdel-Ghany A M, Kozai T. Cooling efficiency of fogging systems for greenhouses. Biosystems Engineering, 2006; 94(1): 97–109.
- [71] Standard A. Heating, ventilating and cooling greenhouses. American Society of Agricultural and Biological Engineers, 2008; 2015: 1.
- [72] Kittas C, Katsoulas N, Baille A. SE-Structures and environment: Influence of greenhouse ventilation regime on the microclimate and energy partitioning of a rose canopy during summer conditions. Journal of Agricultural Engineering Research, 2001; 79(3): 349–360.
- [73] Jain D, Tiwari G N. Modeling and optimal design of evaporative cooling system in controlled environment greenhouse. Energy Conversion and Management, 2002; 43(16): 2235–2250.
- [74] Petek M, Dikmen S, Oğan M M. Performance analysis of a two stage pad cooling system in broiler houses. Turkish Journal of Veterinary and Animal Sciences, 2012; 36(1): 21–26.
- [75] Willits D H. Cooling fan-ventilated greenhouses: A modelling study. Biosystems Engineering, 2003; 84(3): 315–329.
- [76] Max J F J, Horst W J, Mutwiwa U N, Tantau H-J. Effects of greenhouse cooling method on growth, fruit yield and quality of tomato (*Solanum lycopersicum* L.) in a tropical climate. Scientia Horticulturae, 2009; 122(2): 179–186.
- [77] Molina-Aiz F D, Valera D L, Peña A A, Gil J A, López A. A study of natural ventilation in an Almer á-type greenhouse with insect screens by means of tri-sonic anemometry. Biosystems Engineering, 2009; 104(2): 224–242.
- [78] Rigakis N, Katsoulas N, Teitel M, Bartzanas T, Kittas C. A simple model for ventilation rate determination in screenhouses. Energy and Buildings, 2015; 87: 293–301.
- [79] Ganguly A, Ghosh S. A review of ventilation and cooling technologies in agricultural greenhouse application. Iranica Journal of Energy & Environment, 2011; 2(1): 32–46.
- [80] Du K, Sun Z, Han H, Liu S. Development of a web-based wireless telemonitoring system for agro-environment. Computer and Computing Technologies in Agriculture, Volume II, Boston, MA: Springer US, 2008.
- [81] Beccali G, Cellura M, Culotta S, Lo Brano V, Marvuglia A. A web-based autonomous weather monitoring system of the town of palermo and its utilization for temperature nowcasting. Computational Science and Its Applications – ICCSA 2008, Berlin, Heidelberg: Springer Berlin Heidelberg, 2008.
- [82] Okayasu T, Yamabe N, Marui A, Miyazaki T, Mitsuoka M, Inoue E. Development of field monitoring and work recording system in agriculture. Proc. 5th Int. Symp. Mach. Mech. Agr. Biosys. Engng. (ISMAB), CD-ROM, 2010.
- [83] Nugroho A P, Okayasu T, Inoue E, Hirai Y, Mitsuoka M. Development of actuation framework for agricultural informatization supporting system. IFAC Proceedings Volumes, 2013; 46(4): 181–6.
- [84] Dumitraşcu A, Ştefănoiu D, Culiţă J. Remote monitoring and control system for environment applications. Advances in Intelligent Control Systems and Computer Science, 2013: 223–34.
- [85] Gaddam A. Designing a wireless sensors network for monitoring and predicting droughts. ICST 2014 : 8th International Conference on Sensing Technology, Liverpool, UK, 2014.
- [86] Fukatsu T, Kiura T, Hirafuji M. A web-based sensor network system with distributed data processing approach via web application. Computer Standards & Interfaces, 2011; 33(6): 565–573.
- [87] Mizoguchi M, Ito T, Chusul A, Mitsuishi S, Akazawa M. Quasi real-time field network system for monitoring remote agricultural fields. SICE Annual Conference, 2011.
- [88] Arif C, Setiawan B I, Mizoguchi M, Saptomo S K, Sutoyo S, Liyantono L, et al. Performance of quasi-real-time paddy field monitoring systems in Indonesia. Proceedings of the Asia-Pacific Advanced Network, 2014; 37: 10–19.
- [89] Kaloxylas A, Eigenmann R, Teye F, Politopoulou Z, Wolfert S, Shrank C, et al. Farm management systems and the future internet era. Computers and Electronics in Agriculture, 2012; 89: 130–144.
- [90] Kaloxylas A, Groumas A, Sarris V, Katsikas L, Magdalinos P, Antoniou E, et al. A cloud-based farm management system: Architecture and implementation. Computers and Electronics in Agriculture, 2014; 100: 168–179.
- [91] Prima A, Okayasu T, Hoshi T, Inoue E, Hirai Y, Mitsuoka M, et al. Development of a remote environmental monitoring and control framework for tropical horticulture and verification of its validity under unstable network connection in rural area. Computers and Electronics in Agriculture, 2016; 124: 325–339.
- [92] Seródio C, Boaventura Cunha J, Morais R, Couto C, Monteiro J. A networked platform for agricultural management systems. Computers and Electronics in Agriculture, 2001; 31(1): 75–90.
- [93] Morais R, Fernandes M A, Matos S G, Seródio C, Ferreira P J S G, Reis M J C S. A ZigBee multi-powered wireless acquisition device for remote sensing applications in precision viticulture. Computers and Electronics in Agriculture, 2008; 62(2): 94–106.
- [94] López Riquelme J A, Soto F, Suard áz J, Sánchez P, Iborra A, Vera J A. Wireless Sensor Networks for precision horticulture in Southern Spain. Computers and Electronics in Agriculture, 2009; 68(1): 25–35.
- [95] Li T, Zhang M, Ji Y H, Sha S, Jiang Y Q, Minzan L. Management of CO<sub>2</sub> in a tomato greenhouse using WSN and BPNN techniques. Int J Agric & Biol Eng, 2015; 8(4): 43–51.
- [96] Tzounis A, Bartzanas T, Kittas C, Katsoulas N, Ferentinis K P. Spatially distributed greenhouse climate control based on wireless sensor network measurements. International Symposium on Applications of Modelling as an Innovative Technology in the Horticultural Supply Chain, 2015; 111–120.
- [97] Ji Y H, Jiang Y Q, Li T, Zhang M, Sha S, Li M Z. An improved method for prediction of tomato photosynthetic rate based on WSN in greenhouse. Int J Agric & Biol Eng, 2016; 9(1): 146–152.
- [98] Pahuja R, Verma H K, Uddin M. A wireless sensor network for greenhouse climate control. IEEE Pervasive Computing, 2013; 12(2): 49–58.
- [99] Hebel M A, Tate R F, Watson D G. Results of wireless sensor network transceiver testing for agricultural applications. 2007 ASAE Annual Meeting; St. Joseph, MI: ASABE, 2007.
- [100] Chen Y, Shi Y L, Wang Z Y, Huang L. Connectivity of wireless sensor networks for plant growth in greenhouse. Int J Agric & Biol Eng, 2016; 9(1): 89–98.
- [101] Zhou Y, Yang X, Guo X, Zhou M, Wang L. A design of greenhouse monitoring & control system based on zigbee wireless sensor network. Wireless Communications, Networking and Mobile Computing, International Conference on IEEE, 2007: 2563–2567.
- [102] Azaza M, Tanougast C, Fabrizio E, Mami A. Smart greenhouse fuzzy logic based control system enhanced with wireless data monitoring. ISA transactions, 2016; 61: 297–307.
- [103] Gubbi J, Buyya R, Marusic S, Palaniswami M. Internet of things (IoT): A vision, architectural elements, and future directions. Future Generation Computer Systems, 2013; 29(7): 1645–1660.
- [104] Atzori L, Iera A, Morabito G. The internet of things: A survey. Computer Networks, 2010; 54(15): 2787–2805.
- [105] Jin J, Gubbi J, Marusic S, Palaniswami M. An information framework for creating a smart city through internet of things. IEEE Internet of Things Journal, 2014; 1(2): 112–121.
- [106] Liao S-H, Chu P-H, Hsiao P-Y. Data mining techniques and applications – A decade review from 2000 to 2011. Expert Systems with Applications, 2012; 39(12): 11303–11311.
- [107] Chung B-K, Xia C, Song Y-H, Lee J-M, Li Y, Kim H, et al. Sampling of *Bemisia tabaci* adults using a pre-programmed autonomous pest control robot. Journal of Asia-Pacific Entomology, 2014; 17(4): 737–743.

- [108] He D, Zeadally S. An analysis of RFID authentication schemes for internet of things in healthcare environment using elliptic curve cryptography. *IEEE Internet of Things Journal*, 2015; 2(1): 72–83.
- [109] Miorandi D, Sicari S, de Pellegrini F, Chlamtac I. Internet of things: Vision, applications and research challenges. *Ad Hoc Networks*, 2012; 10(7): 1497–1516.
- [110] Najera P, Lopez J, Roman R. Real-time location and inpatient care systems based on passive RFID. *Journal of Network and Computer Applications*, 2011; 34(3): 980–989.
- [111] Liao M-S, Chen S-F, Chou C-Y, Chen H-Y, Yeh S-H, Chang Y-C, et al. On precisely relating the growth of *Phalaenopsis* leaves to greenhouse environmental factors by using an IoT-based monitoring system. *Computers and Electronics in Agriculture*, 2017; 136: 125–139.
- [112] Peng G, Lahlali R, Hwang S-F, Pageau D, Hynes R K, McDonald M R, et al. Crop rotation, cultivar resistance, and fungicides/biofungicides for managing clubroot (*Plasmiodiophora brassicae*) on canola. *Canadian Journal of Plant Pathology*, 2014; 36(sup1): 99–112.
- [113] Lin M-J, Hsu B-D. Photosynthetic plasticity of *Phalaenopsis* in response to different light environments. *Journal of Plant Physiology*, 2004; 161(11): 1259–1268.
- [114] Caponetto R, Fortuna L, Nunnari G, Occhipinti L. A fuzzy approach to greenhouse climate control. *Proceedings of the American Control Conference*, 1998; 3: 1866–1870.
- [115] Pan L F, Wang W L, Wu Q D. Application of adaptive fuzzy logic system to model for greenhouse climate. *Intelligent Control and Automation*, 2000 Proceedings of the 3rd World Congress, 2000; 3(1): 1687–1691.
- [116] Lin C J. A GA-based neural fuzzy system for temperature control. *Fuzzy Sets and Systems*, 2004; 143(2): 311–333.
- [117] Castañeda-Miranda R, Ventura-Ramos E, del Roc ó Peniche-Vera R, Herrera-Ruiz G. Fuzzy greenhouse climate control system based on a field programmable gate array. *Biosystems Engineering*, 2006; 94(2): 165–177.
- [118] Xu F, Sheng J Q, Chen J L. Rough sets based fuzzy logic control for greenhouse temperature. 2006 2nd IEEE/ASME International Conference on Mechatronics and Embedded Systems and Applications, 2006.
- [119] 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(Supplement C): 110–133.
- [120] Shamsiri 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. In: Jurić S. *Plant Engineering*. Rijeka: InTech, 2017; p.9.
- [121] Impron I, Hemming S, Bot G P A. Simple greenhouse climate model as a design tool for greenhouses in tropical lowland. *Biosystems Engineering*, 2007; 98(1): 79–89.
- [122] Lu N, Nukaya T, Kamimura T, Zhang D, Kurimoto I, Takagaki M et al. Control of vapor pressure deficit (VPD) in greenhouse enhanced tomato growth and productivity during the winter season. *Scientia Horticulturae*, 2015; 197: 17–23.
- [123] Lafont F, Balmat J F, Pessel N, Fliess M. A model-free control strategy for an experimental greenhouse with an application to fault accommodation. *Computers and Electronics in Agriculture*, 2015; 110: 139–149.
- [124] Gruber J K, Guzmán J L, Rodríguez F, Bordons C, Berenguel M, Sánchez J A. Nonlinear MPC based on a Volterra series model for greenhouse temperature control using natural ventilation. *Control Engineering Practice*, 2011; 19(4): 354–366.
- [125] Speetjens S L, Stigter J D, van Straten G. Towards an adaptive model for greenhouse control. *Computers and Electronics in Agriculture*, 2009; 67(1-2): 1–8.
- [126] Bennis N, Duplaix J, En é G, Haloua M, Youlal H. Greenhouse climate modelling and robust control. *Computers and Electronics in Agriculture*, 2008; 61(2): 96–107.
- [127] Fleisher D H, Baruh H. An optimal control strategy for crop growth in advanced life support systems. *Life Support & Biosphere Science*, 2001; 8(1): 43–53.
- [128] Van Ooteghem R J C. Optimal control design for a solar greenhouse. *IFAC Proceedings Volumes*, 2010; 43(26): 304–309.
- [129] Van Henten E J, Bontsema J. Time-scale decomposition of an optimal control problem in greenhouse climate management. *Control Engineering Practice*, 2009; 17(1): 88–96.
- [130] Ioslovich I, Gutman P O, Linker R. Hamilton-Jacobi-Bellman formalism for optimal climate control of greenhouse crop. *Automatica*, 2009; 45(5): 1227–1231.
- [131] Van Beveren P J M, Bontsema J, van Straten G, van Henten E J. Optimal control of greenhouse climate using minimal energy and grower defined bounds. *Applied Energy*, 2015; 159: 509–519.
- [132] Van Beveren P J M, Bontsema J, van Straten G, van Henten E J. Minimal heating and cooling in a modern rose greenhouse. *Applied Energy*, 2015; 137: 97–109.
- [133] Sanchez-Molina J A, Li M, Rodriguez F, Guzman J L, Wang H, Yang X T. Development and test verification of air temperature model for Chinese solar and Spanish Almeria-type greenhouses. *Int J Agric & Biol Eng*, 2017; 10(4): 66–76.
- [134] Blasco X, Martínez M, Herrero J M, Ramos C, Sanchis J. Model-based predictive control of greenhouse climate for reducing energy and water consumption. *Computers and Electronics in Agriculture*, 2007; 55(1): 49–70.
- [135] Ji R, Qi L, Huo Z. Design of fuzzy control algorithm for precious irrigation system in greenhouse. *Computer and Computing Technologies in Agriculture V*, Berlin, Heidelberg: Springer Berlin Heidelberg, 2012.
- [136] Márquez-Vera M A, Ramos-Fernández J C, Cerecero-Natale L F, Lafont F, Balmat J-F, Esparza-Villanueva J I. Temperature control in a MISO greenhouse by inverting its fuzzy model. *Computers and Electronics in Agriculture*, 2016; 124: 168–174.
- [137] El-Madbouly E I, Hameed I A, Abdo M I. Reconfigurable adaptive fuzzy fault-hiding control for greenhouse climate control system. *International Journal of Automation and Control*, 2017; 11(2): 164–187.
- [138] Nachidi M, Rodríguez F, Tadeo F, Guzman J L. TakagiSugeno control of nocturnal temperature in greenhouses using air heating. *ISA Transactions*, 2011; 50(2): 315–320.
- [139] Liu X-W, Dai T-F. Design for fuzzy decoupling control system of temperature and humidity. *Advanced Research on Computer Science and Information Engineering*, Berlin, Heidelberg: Springer Berlin Heidelberg, 2011.
- [140] Vadiée A, Martin V. Energy management in horticultural applications through the closed greenhouse concept, state of the art. *Renewable and Sustainable Energy Reviews*, 2012; 16(7): 5087–5100.
- [141] Ghasemi Mobtaker H, Ajabshirchi Y, Ranjbar S F, Matloobi M. Solar energy conservation in greenhouse: Thermal analysis and experimental validation. *Renewable Energy*, 2016; 96(Part A): 509–519.
- [142] Taki M, Rohani A, Rahmati-joneidabad M. Solar thermal simulation and applications in greenhouse. *Information Processing in Agriculture*, 2017.
- [143] Ha T, Lee I-B, Kwon K-S, Hong S-W. Computation and field experiment validation of greenhouse energy load using building energy simulation model, 2015; 8(6): 116–127.
- [144] 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. *Int J Agric & Biol Eng*, 2014; 7(1): 1–16.
- [145] 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.
- [146] Xu J, Li Y, Wang R Z, Liu W, Zhou P. Experimental performance of evaporative cooling pad systems in greenhouses in humid subtropical climates. *Applied Energy*, 2015; 138: 291–301.
- [147] Espinoza K, Valera D L, Torres J A, López A, Molina-Aiz F D. An Auto-tuning pi control system for an open-circuit low-speed wind tunnel designed for greenhouse technology. *Sensors*, 2015: 19723–19749.
- [148] Ioslovich I, Gutman P-O, Linker R. Hamilton-Jacobi-Bellman formalism for optimal climate control of greenhouse crop. *Automatica*, 2009; 45(5): 1227–1231.
- [149] Van Beveren P, Bontsema J, van Straten G, van Henten E J. Minimal heating and cooling in a modern rose greenhouse. *IFAC Proceedings Volumes*, 2013; 46(18): 282–287.
- [150] 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.
- [151] Incrocci L, Stanghellini C, Kempkes F. Carbon dioxide fertilization in Mediterranean greenhouses: When and how is it economical? *International Symposium on Strategies Towards Sustainability of Protected Cultivation in Mild Winter Climate 807*, 2008.
- [152] Linker R, Seginer I, Gutman P. Optimal CO<sub>2</sub> control in a greenhouse



- modeled with neural networks. *Computers and Electronics in Agriculture*, 1998; 19(3): 289–310.
- [153] 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.
- [154] Nadal A, Llorach-Massana P, Cuerva E, López-Capel E, Montero J I, Josa A, et al. Building-integrated rooftop greenhouses: An energy and environmental assessment in the mediterranean context. *Applied Energy*, 2017; 187: 338–351.
- [155] Vadiee A, Martin V. Thermal energy storage strategies for effective closed greenhouse design. *Applied Energy*, 2013; 109: 337–343.
- [156] Vadiee A, Martin V. Energy analysis and thermoeconomic assessment of the closed greenhouse-The largest commercial solar building. *Applied Energy*, 2013; 102: 1256–1266.
- [157] Heuvelink E, Bakker M, Marcelis L, Raaphorst M. Climate and yield in a closed greenhouse. *Acta Horticulturae*, 2008; 801: 1083–1092.
- [158] Farzaneh-Gord M, Arabkoohsar A, Deymi Dashtebayaz M, Khoshnevis A A. New method for applying solar energy in greenhouses to reduce fuel consumption. *Int J Agric & Biol Eng*, 2013; 6(4): 64–75.
- [159] Van Den Bulck N, Coomans M, Wittemans L, Hanssens J, Steppe K. Monitoring and energetic performance analysis of an innovative ventilation concept in a Belgian greenhouse. *Energy and Buildings*, 2013; 57: 51–57.
- [160] Kittas C, Bartzanas T. Greenhouse microclimate and dehumidification effectiveness under different ventilator configurations. *Building and Environment*, 2007; 42(10): 3774–3784.
- [161] Mashonjowa E, Ronsse F, Milford J R, Pieters J G. Modelling the thermal performance of a naturally ventilated greenhouse in Zimbabwe using a dynamic greenhouse climate model. *Solar Energy*, 2013; 91: 381–393.
- [162] Wu F-Q, Zhang L-B, Xu F, Ai Q-L, Chen J-L. Numerical modeling and analysis of the environment in a mechanically ventilated greenhouse. *Proceedings of SPIE*, 2009; 7491(1): 749106–749108.
- [163] DAYIOĞLU M A. Performance analysis of a greenhouse fan-pad cooling system: gradients of horizontal temperature and relative humidity. *Tarım Bilimleri Dergisi*, 2015; 21(1): 132–143.
- [164] Fuchs M, Dayan E, Presnov E. Evaporative cooling of a ventilated greenhouse rose crop. *Agricultural and Forest Meteorology*, 2006; 138(1): 203–215.
- [165] Montero J I. Evaporative cooling in greenhouses: Effect on microclimate, water use efficiency and plant respons. *International Society for Horticultural Science (ISHS)*, Leuven, Belgium, 2006.
- [166] Jain D. Development and testing of two-stage evaporative cooler. *Building and Environment*, 2007; 42(7): 2549–2554.
- [167] Jamaludin D, Ahmad D, Kamaruddin R, Jaafar H Z E. Microclimate inside a tropical greenhouse equipped with evaporative cooling pads. *Pertanika Journal of Science and Technology*, 2014; 22(1): 255–272.
- [168] Villarreal-Guerrero F, Kacira M, Fitz-Rodríguez E, Kubota C, Giacomelli G A, Linker R, et al. Comparison of three evapotranspiration models for a greenhouse cooling strategy with natural ventilation and variable high pressure fogging. *Scientia Horticulturae*, 2012; 134: 210–221.
- [169] Shamshiri R, Ismail W I W. A review of greenhouse climate control and automation systems in tropical regions. *J Agric Sci Appl*, 2013; 2(3): 176–183.
- [170] Li T, Ji Y H, Zhang M, Sha S, Li M Z. Universality of an improved photosynthesis prediction model based on PSO-SVM at all growth stages of tomato. *Int J Agric & Biol Eng*, 2017; 10(2): 63–73.
- [171] Baptista F J F. Modelling the climate in unheated tomato greenhouses and predicting *Botrytis cinerea* infection. *Universidade de Evora (Portugal)*, 2007.
- [172] 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(2): 217–227.
- [173] Takakura T. Technical models of the greenhouse environment. *International Society for Horticultural Science (ISHS)*, Leuven, Belgium, 1989.
- [174] Tap R F. Economics-based optimal control of greenhouse tomato crop production. *Wageningen University*, 2000.
- [175] Van Henten E J. Sensitivity analysis of an optimal control problem in greenhouse climate management. *Biosystems Engineering*, 2003; 85(3): 355–364.
- [176] Luo W, de Zwart H F, Dail 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(3): 307–318.
- [177] Sethi V P, Dubey R K, Dhath A S. Design and evaluation of modified screen net house for off-season vegetable raising in composite climate. *Energy Conversion and Management*, 2009; 50(12): 3112–3128.
- [178] Fitz-Rodríguez E, Kubota C, Giacomelli G A, Tignor M E, Wilson S B, McMahon M. Dynamic modeling and simulation of greenhouse environments under several scenarios: A web-based application. *Computers and Electronics in Agriculture*, 2010; 70(1): 105–116.
- [179] Panwar N L, Kaushik S C, Kothari S. Solar greenhouse an option for renewable and sustainable farming. *Renewable and Sustainable Energy Reviews*, 2011; 15(8): 3934–3945.
- [180] Nebbali R, Roy J C, Boulard T. Dynamic simulation of the distributed radiative and convective climate within a cropped greenhouse. *Renewable Energy*, 2012; 43: 111–129.
- [181] Yu H, Chen Y, Hassan S G, Li D. Prediction of the temperature in a Chinese solar greenhouse based on LSSVM optimized by improved PSO. *Computers and Electronics in Agriculture*, 2016; 122: 94–102.
- [182] De Zwart H F. Analyzing energy-saving options in greenhouse cultivation using a simulation model. *De Zwart*, 1996.
- [183] Graamans L, Baeza E, van den Dobbelsteen A, Tsafaras I, Stanghellini C. Plant factories versus greenhouses: Comparison of resource use efficiency. *Agricultural Systems*, 2018; 160: 31–43.
- [184] Gary C, Jones J W, Tchamitchian M. Crop modelling in horticulture: State of the art. *Scientia Horticulturae*, 1998; 74(1-2): 3–20.
- [185] Heuvelink E. Evaluation of a dynamic simulation model for tomato crop growth and development. *Annals of Botany*, 1999; 83(4): 413–422.
- [186] Gary C, Baille A, Navarrete M, Espanet R. TOMPOUSSE, un modèle simplifié de prévision du rendement et du calibre de la tomate. *Actes du Séminaire de l'AIP intersectorielle "Serres"*, INRA, Avignon, 1997: 100–109.
- [187] Abreu P, Meneses J F, Gary C. Tompousse, a model of yield prediction for tomato crops: calibration study for unheated plastic greenhouses. *International Society for Horticultural Science (ISHS)*, Leuven, Belgium, 2000.
- [188] Jones J W, Dayan E, Allen L H, van Keulen H, Challa H. A dynamic tomato growth and yield model (TOMGRO). *Transactions of the ASAE*, 1991; 34(2): 663–672.
- [189] Jones J W, Kenig A, Vallejos C E. Reduced state-variable tomato growth model. *Transactions of the ASAE*, 1999; 42(1): 255–265.
- [190] Kenig A. TOMGRO v3. 0 A dynamic model of tomato growth and yield. Ch. II-5 In: *Optimal environmental control for indeterminate greenhouse crops*. Seginer I, Jones J W, Gutman P, Vallejos C E. BARD Research Report No. IS-1995-91RC. Haifa, 1997.
- [191] Cooman A, Medina A, Schrevels E, Tenorio J. Simulation of greenhouse management for the cultivation of tomato in the high altitude tropics. *International Society for Horticultural Science (ISHS)*, Leuven, Belgium, 2005.
- [192] Gallardo M, Thompson R B, Rodríguez J S, Rodríguez F, Fernández M D, Sánchez J A, et al. Simulation of transpiration, drainage, N uptake, nitrate leaching, and N uptake concentration in tomato grown in open substrate. *Agricultural Water Management*, 2009; 96(12): 1773–1784.
- [193] Shamshiri R, Ahmad D, Ishak Wan Ismail W, Che Man H, Zakaria A, Yamin M, et al. Comparative evaluation of naturally ventilated screenhouse and evaporative cooled greenhouse based on optimal vapor pressure deficit. 2016 ASABE Annual International Meeting, St. Joseph, MI: ASABE, 2016; 1.
- [194] Ehret D L, Hill B D, Helmer T, Edwards D R. Neural network modeling of greenhouse tomato yield, growth and water use from automated crop monitoring data. *Computers and Electronics in Agriculture*, 2011; 79(1): 82–89.
- [195] Clarke N D, Shipp J L, Papadopoulos A P, Jarvis W R, Khosla S, Jewett T J, et al. Development of the harrow greenhouse manager: A decision-support system for greenhouse cucumber and tomato. *Computers and Electronics in Agriculture*, 1999; 24(3): 195–204.
- [196] Gupta M K, Samuel D V K, Sirohi N P S. Decision support system for greenhouse seedling production. *Computers and Electronics in Agriculture*, 2010; 73(2): 133–145.
- [197] Pawlowski A, Sánchez-Molina J A, Guzmán J L, Rodríguez F, Dormido S. Evaluation of event-based irrigation system control scheme for tomato crops in greenhouses. *Agricultural Water Management*, 2017; 183: 16–25.

- [198] Sánchez-Molina J A, Pérez N, Rodríguez F, Guzmán J L, López J C. Support system for decision making in the management of the greenhouse environmental based on growth model for sweet pepper. *Agricultural Systems*, 2015; 139: 144–152.
- [199] Fisher P R, Heins R D, Ehler N, Lieth J H. A decision-support system for real-time management of Easter lily (*Lilium longiflorum Thunb.*) scheduling and height-I. System description. *Agricultural Systems*, 1997; 54(1): 23–37.
- [200] Sun Z F, Zhang Z B, Tong C F. Development of a real time on-line aided decision-making support system for greenhouse tomato production. *Transaction of CSAE*, 2001; 17(7): 75–78. (in Chinese)
- [201] Tchamitchian M, Martin-Clouaire R, Lagier J, Jeannequin B, Mercier S. SERRISTE: A daily set point determination software for glasshouse tomato production. *Computers and Electronics in Agriculture*, 2006; 50(1): 25–47.
- [202] Körner OSGV. Decision support for dynamic greenhouse climate control strategies. *Computers and Electronics in Agriculture*, 2008; 60: 18–30.
- [203] Cañadas J, Sánchez-Molina J A, Rodríguez F, del Águila I M. Improving automatic climate control with decision support techniques to minimize disease effects in greenhouse tomatoes. *Information Processing in Agriculture*, 2017; 4(1): 50–63.
- [204] Aiello G, Giovino I, Vallone M, Catania P, Argento A. A decision support system based on multisensor data fusion for sustainable greenhouse management. *Journal of Cleaner Production*, 2018; 172: 4057–4065.
- [205] Short T H, Draper C M, Donnell M A. Web-based decision support system for hydroponic vegetable production. *International Conference on Sustainable Greenhouse Systems-Greensys*, 2004: 867–870.
- [206] El-Attal A H. Decision model for hydroponic tomato production (hytmod) using utility theory. The Ohio State University, 1995.
- [207] Shamshiri R, Che Man H, Zakaria A J, Beveren P V, Wan Ismail W I, Ahmad D. Membership function model for defining optimality of vapor pressure deficit in closed-field cultivation of tomato. *International Society for Horticultural Science (ISHS)*, Leuven, Belgium, 2017.
- [208] Shamshiri R, van Beveren P, Che Man H, Zakaria A J. Dynamic Assessment of air temperature for tomato (*Lycopersicon esculentum Mill*) cultivation in a naturally ventilated net-screen greenhouse under tropical lowlands climate. *Journal of Agricultural Science and Technology*, 2017; 19(1): 59–72.
- [209] Ellis J. Agricultural transparency: Reconnecting urban centres with food production, 2012.
- [210] Abel C. The vertical garden city: towards a new urban topology. *CTBUH Journal*, 2010; 2: 20–30.
- [211] Despommier D. The vertical farm: Feeding the world in the 21st century. Macmillan, 2010.
- [212] Caplow T. Building integrated agriculture: Philosophy and practice. *Urban Futures*, 2009; 2030: 48–51.
- [213] Thomaier S, Specht K, Henckel D, Dierich A, Siebert R, Freisinger U B, et al. Farming in and on urban buildings: Present practice and specific novelties of Zero-Acreage Farming (ZFarming). *Renewable Agriculture and Food Systems*, 2015; 30(1): 43–54.
- [214] Mok H-F, Williamson V G, Grove J R, Burry K, Barker S F, Hamilton A J. Strawberry fields forever? Urban agriculture in developed countries: A review. *Agronomy for Sustainable Development*, 2014; 34(1): 21–43.
- [215] Taylor J R, Lovell S T. Mapping public and private spaces of urban agriculture in Chicago through the analysis of high-resolution aerial images in Google Earth. *Landscape and Urban Planning*, 2012; 108(1): 57–70.
- [216] Benis K, Ferrão P. Potential mitigation of the environmental impacts of food systems through urban and peri-urban agriculture (UPA) – A life cycle assessment approach. *Journal of Cleaner Production*, 2017; 140: 784–795.
- [217] Pöding B, Mergenthaler M, Lörleberg W. Professional urban agriculture and its characteristic business models in Metropolis Ruhr, Germany. *Land Use Policy*, 2016; 58: 366–379.
- [218] Cahya D L. Analysis of urban agriculture sustainability in metropolitan Jakarta (Case study: Urban agriculture in Duri Kosambi). *Procedia - Social and Behavioral Sciences*, 2016; 227: 95–100.
- [219] Ahlström L, Zahra M. Integrating a greenhouse in an urban area. Unpublished master's thesis, Chalmers University of Technology, Göteborg, Sweden, 2011.
- [220] Kaplan PBT-DM. Encyclopedia of food and agricultural ethics. 2014.
- [221] Besthorn F H. Vertical farming: Social work and sustainable urban agriculture in an age of global food crises. *Australian Social Work*, 2013; 66(2): 187–203.
- [222] Holloway M. The glass house in the desert. *Scientific American*, 2002; 286(1): 90–92.
- [223] Lehmann S, Yeang K. Meeting with the green urban planner: a conversation between Ken Yeang and Steffen Lehmann on eco-masterplanning for green cities. *Journal of Green Building*, 2010; 5(1): 36–40.
- [224] Kim H-G, Park D-H, Chowdhury O R, Shin C-S, Cho Y-Y, Park J-W. Location-based intelligent robot management service model using RGPSi with AoA for vertical farm. *Advances in Computer Science and its Applications*, Berlin, Heidelberg: Springer Berlin Heidelberg, 2014.
- [225] Banerjee C, Adenauer L. Up, up and away! The economics of vertical farming. *Journal of Agricultural Studies*, 2014; 2(1): 40–60.
- [226] Joachim S. Skyfarming: An alternative to horizontal croplands. *Resource Magazine*, 2011.
- [227] Germer J, Sauerborn J, Asch F, de Boer J, Schreiber J, Weber G, et al. Skyfarming an ecological innovation to enhance global food security. *Journal für Verbraucherschutz und Lebensmittelsicherheit*, 2011; 6(2): 237.
- [228] Sivamani S, Bae N, Cho Y. A smart service model based on ubiquitous sensor networks using vertical farm ontology. *International Journal of Distributed Sensor Networks*, 2013.
- [229] Al-Chalabi M. Vertical farming: Skyscraper sustainability? *Sustainable Cities and Society*, 2015; 18: 74–77.
- [230] Miller A. Scaling up or selling out?: A critical appraisal of current developments in vertical farming. Carleton University, 2011.
- [231] Kalantari F, Mohd Tahir O, Mahmoudi Lahijani A, Kalantari S. A review of vertical farming technology: A guide for implementation of building integrated agriculture in cities. *Trans Tech Publ*, 2017.
- [232] Liu X. Design of a modified shipping container as modular unit for the minimally structured & modular vertical farm (MSM-VF): The University of Arizona, 2014.
- [233] Montero J I, Baeza E, Heuvelink E, Rieradevall J, Muñoz P, Ercilla M. Productivity of a building-integrated roof top greenhouse in a Mediterranean climate. *Agricultural Systems*, 2017; 158: 14–22.
- [234] Pons O, Nadal A, Sanyémengual E, Llorach-massana P, Rosa M. Roofs of the future: Rooftop greenhouses to improve buildings metabolism. *Procedia Engineering*, 2015; 123: 441–448.
- [235] Sanyémengual E, Cerón-Palma I, Oliver-Solà J, Montero J I, Rieradevall J. Integrating horticulture into cities: A guide for assessing the implementation potential of rooftop greenhouses (RTGs) in industrial and logistics parks. *Journal of Urban Technology*, 2015; 22(1): 87–111.
- [236] Ercilla-Montserrat M, Izquierdo R, Belmonte J, Ignacio J, Muñoz P, Linares C D, et al. Science of the total environment building-integrated agriculture: A first assessment of aerobiological air quality in rooftop greenhouses (i-RTGs). *Science of the Total Environment*, 2017; 598: 109–120.
- [237] Kozai T. Resource use efficiency of closed plant production system with artificial light: Concept, estimation and application to plant factory. *Proceedings of the Japan Academy, Series B*, 2013; 89(10): 447–461.
- [238] Glaser J A. Green chemistry with nanocatalysts. *Clean Technologies and Environmental Policy*, 2012; 14(4): 513–520.
- [239] Miyagi A, Uchimiya H, Kawai-Yamada M. Synergistic effects of light quality, carbon dioxide and nutrients on metabolite compositions of head lettuce under artificial growth conditions mimicking a plant factory. *Food Chemistry*, 2017; 218: 561–568.
- [240] Shimokawa A, Tonooka Y, Matsumoto M, Ara H, Suzuki H, Yamauchi N, et al. Effect of alternating red and blue light irradiation generated by light emitting diodes on the growth of leaf lettuce. *bioRxiv*, 2014.
- [241] García-Fraile P, Menéndez E, Rivas R. Role of bacterial biofertilizers in agriculture and forestry. *AIMS Bioengineering*, 2015; 2(3): 183–205.
- [242] Kalantari F, Tahir O M, Joni R A, Fatemi E. Opportunities and challenges in sustainability of vertical farming: A review. *Journal of Landscape Ecology*, 2017: 5–30.
- [243] Eigenbrod C, Gruda N. Urban vegetable for food security in cities: A review. *Agronomy for Sustainable Development*, 2015; 35(2): 483–498.
- [244] Zoll F, Specht K, Siebert R. Innovation in urban agriculture: Evaluation data of a participatory approach (ROIR). *Data in Brief*, 2016; 7: 1473–1476.
- [245] Despommier D. Farming up the city: The rise of urban vertical farms. *Trends in Biotechnology*, 2013; 31(7): 388–389.
- [246] Voss P M. Vertical farming: An agricultural revolution on the rise. *Halmstad*, 2013.