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

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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

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1 Introduction

Closed-field agriculture is experiencing a breakthrough 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[1]. 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[10] and Critten and Bailey[11].

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,

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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.[1] 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.[1] 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.[1] 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[12]. 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[13,14] 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.[15]. 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.

a. A typical multi-span structures of Dutch greenhouse with glass panel for large-scale commercial production

b. A multi-span Quonset tropical greenhouse structure with insect-proof mesh screens

c. A modern Gable greenhouse with rooftop solar panels

d. A plant factory with artificial light

e. A commercial smart greenhouse with Internet-of-Things monitoring

f. A robotic nursery greenhouse for automated spraying and management

g. A modular greenhouse used in urban farming

h. A high-tech agri-cube personal vegetable cultivation factory

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.[16] recommended that in order to obtain a reasonable heat rise of less than 4℃ in a glass-clad greenhouse, the airflow rate should be 0.04-0.05 m^3/s of floor area (1 m^2). 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[17,18], double-wall plastic[19,20], and glass[21,22], to fiberglass[23,24], double-wall plastic, acrylic sheet[25], polyethylene film[26-29], polyvinyl chloride (PVC)[30], copolymers[31], Polycarbonate panels[32], and selective transmission medium[33,34] 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[34].

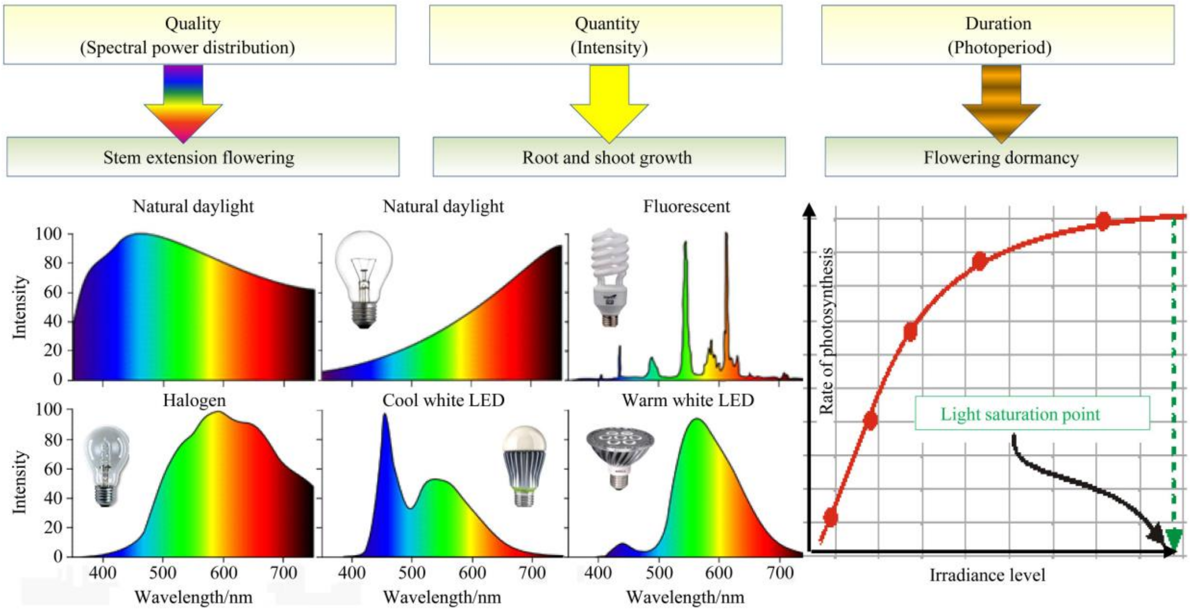
Condensation, radiation transmittance and diffusing properties of different types of transmitting covering materials in greenhouses have been discussed by Pollet et al.[35]. Glazing materials allow shorter-wavelength radiation (i.e. visible light) to pass through, but long wavelength radiation such as 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.[36] and Hemming et al.[37] Jarquín-Enríquez et al.[38] 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℃-33℃, the temperature inside a polyethylene film covered greenhouse without environment control reached 68℃-70℃, leading to air vapor pressure deficit (VPD) of 4 kPa[39]. Al-Mahdouri et al.[40] 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.[41] A computer application to measure geometric characterization and dimensions of insect-proof screens was designed by Álvarez et al.[42]. 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^3/s of floor area (1 m^2)[43]. 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.[44], 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[45] 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℃-3℃ 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[46] 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[39]. Shading nets ease the natural ventilation process and can protect plants from excessive sunlight, wind, and heavy rains. Lorenzo et al.[47] 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[48]. 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[49]. 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_2, 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.



a. Spectral power distribution of natural and artificial light sources (adapted from www.lightingschoo.eu)

b. light response curve of plants (adapted from http://w3.marietta.edu/)

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.[50], 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)[51]. 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[52-54]. In another study, Ilić et al.[55] 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[56] and 35% by El-Gizawy et al.[57] Moreover, El-Gizawy et al.[57] 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[52].

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[58], Cherie[59] and Jones[60]. 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[61]. 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.

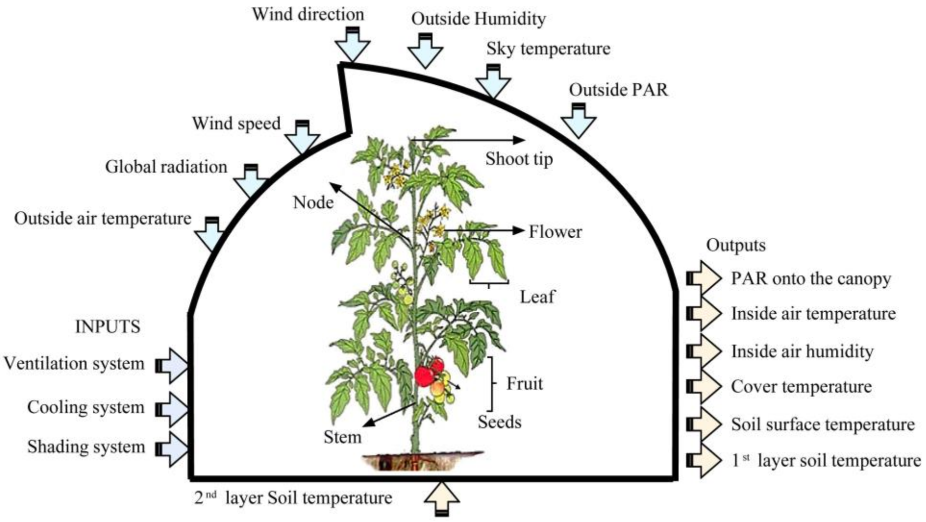


Figure 3 Inputs and outputs of controlled environment agriculture

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[63,64], but research works on their use alongside natural ventilation in greenhouses in semiarid climates are narrow[65]. 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[62]. 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[66]; 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 (m^3/min) of 1 to 1.5 times of the greenhouse volume is recommended every minute[16]. 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.[67], a properly operated typical swamp cooler has the potential to cool air within 3℃ to 4℃ 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 μm. 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[68]. Low and high-pressure fogging systems in a naturally ventilated greenhouse have been studied and compared by Li and Willits[69], 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[70]. The efficiency of an evaporative cooling system is calculated by $\eta=\frac{T_{out}-T_{cool}}{T_{out}-T_{wb}}$ as given in the ASABE standards[71]. Here, T_{out} is the outdoor air temperature, ℃; T_{cool} is the temperature of air exiting the cooling pad, ℃, and T_{wb} is the wet-bulb temperature of the outside air, ℃.

Measurement and data analysis for greenhouse evaporative cooling are discussed in the work of Kittas et al.[72] A decrease in air temperature by 4℃ to 5℃ inside a greenhouse with pad-and-fan evaporative cooling is reported by Jain and Tiwari[73]. Performance of a two-stage pad cooling system in broiler houses was analyzed by Petek et al.[74] 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[75]. 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℃ and a humidity ratios of 3.3 g/kg, to 0.8℃ for an outdoor humidity ratio of 29.9 g/kg at the same air temperature. In another study, Max et al.[76] 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[77,78]. A comprehensive review of ventilation systems is available in the works of Ganguly and Ghosh[79]. 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.

$$\frac{1}{A_i^2}=\frac{1}{A_0^2}=\frac{2g\cdot h\cdot H_P}{T_i(\rho\cdot S\cdot V+W)V^2} \tag{1}$$

$$q_s+q_m+q_{s0}+q_h=(\sum_c(AU)_c+FP+C_p\cdot\rho\cdot V)(t_i-t_0) \tag{2}$$

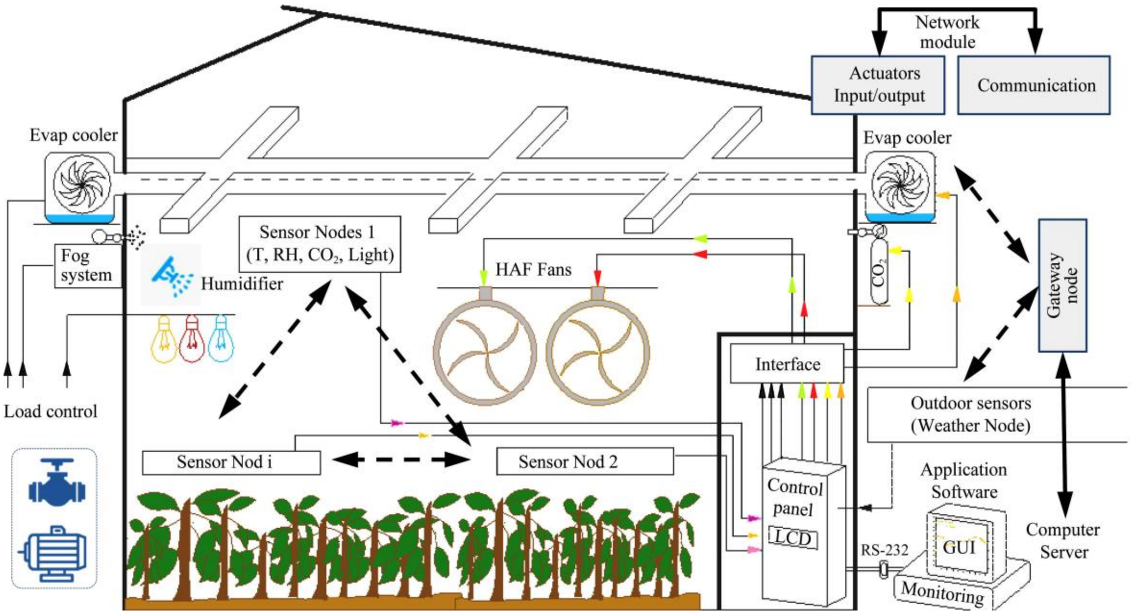
where, A_i is inlet size of natural ventilation, m^2; A_0 is outlet size of natural ventilation, m^2; g is gravity=9.76, m/s^2; h is height difference between inlet to outlet of natural ventilation, m; H_p is heat supplied to the greenhouse structure, W; T_i is absolute temperature in greenhouse, K=(℃ + 273); ρ is density of air in greenhouse, is equal to 1.175 at 25℃, kg/m^3; S is specific heat of air, J/(kg·℃); V is ventilation rate, m^3/s; W is heat loss through greenhouse cover, W/℃; U is overall unit area thermal conductance of component, W/(m^2·K); A is area of structural component, 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), W/(m·K); C_p is specific heat of moist air, J/(kg·K); V is volumetric airflow rate, m^3/s; t_i is indoor temperature, ℃; t_o is outdoor temperature, ℃.

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[80-83], wireless sensor networks[84,85], field-server based monitoring[86], field router systems[87,88], and distributed data acquisition with local control management[89,90]. A comprehensive comparison between the existing remote monitoring system in agricultural research is available in the work of Prima et al.[91] 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.[92] 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[93,94] and in closed-field environment agriculture.



Source: www.AdaptiveAgroTech.com.

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

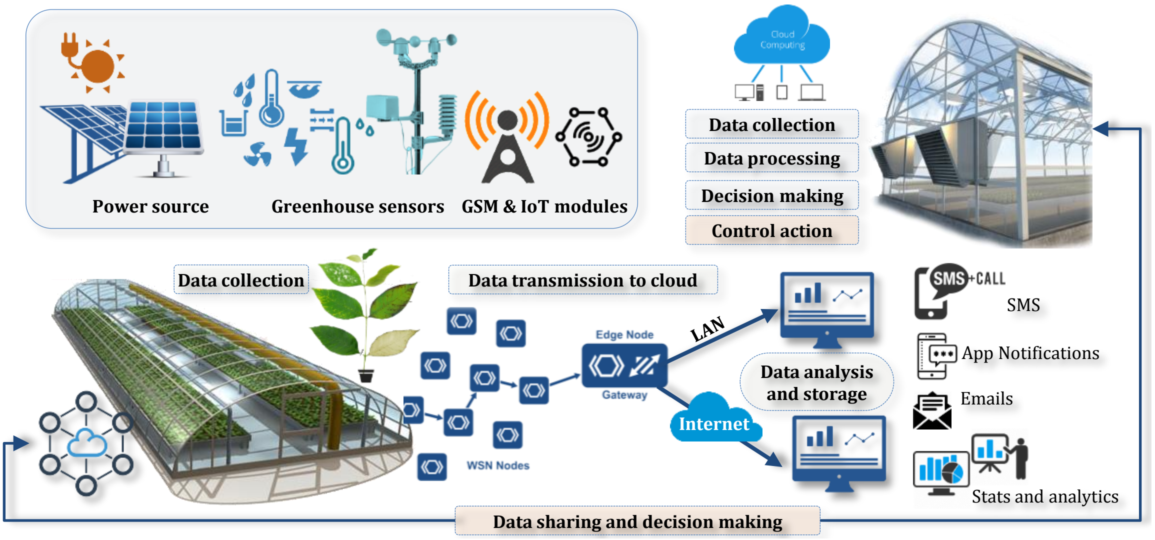
An interesting application of WSN in greenhouse includes CO_2 management[95] and multipoint measurements of microclimate for monitoring spatial gradients and three-dimensional changes in parameters during the cultivation process[96]. For example, Ji et al.[97] developed a WSN for precision control of CO_2 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.[93] 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.[98] 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.[91] 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[99]. 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.[100] 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.[101] More recently, Azaza et al.[102] 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.

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[103]. Both academic and industry sections have shown interest in greenhouse applications of IoT[104]. In fact, IoT has been used in many areas of researchers, such as: smart city[105], agriculture[106,107] and healthcare[108-110], 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[107]. An application of this technology can be found in the work of Liao et al.[111] 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.[112] showed that by using a spectroscopic and spectrometer investigation can correctly provide the total of orchid chlorophyll.

Moreover, Lin and Hsu[113] applied a chlorophyll fluorometer in their study. The 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[109].

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.[114], Pan et al.[115], Lin[116], Castañeda-Miranda et al.[117] and Xu et al.[118] 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[119,120]. The level of approaches vary from simple models and timer-based feedback controls[121,122] to more advanced solutions, such as model-free control strategy[123], nonlinear control methods[124], adaptive control and adaptive management framework[120,125], robust[126], optimal control[127-132], energy balance models[133], and model-based predictive control[134]. 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[135] and microclimate control. Several techniques and approaches have been presented, including inverting fuzzy model[136], reconfigurable adaptive fuzzy fault-hiding control[137], TakagiSugeno fuzzy modeling[138], conventional fuzzy logic control for smart greenhouses[102], and decentralized decoupling fuzzy logic controller[139]. These solutions have shown a more effective set-point tracking compared with the conventional PID controllers. For example, El-Madbouly et al.[137] 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.[102] 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[104] 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[141,142], determining energy load using building energy simulation models[143], computational fluid dynamics method[119,144,145], or providing optimal growth condition with minimum environmental impacts[120,146,147]. Other researchers have proposed optimization methods for maximizing the returns. See for example the works[148] 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.[149] and later expanded in [150] to include humidity balance. Incrocci et al.[151] proposed that optimal CO_2 concentration in the greenhouse can be based on an economic evaluation. To maintain a given CO_2 concentration within the greenhouse, the supply must balance the assimilated CO_2 flux to the outside air due to ventilation. Linker et al.[152] optimized greenhouse operation and in particular CO_2 control, using a neural network. Most of these approaches have used crop models and prices of the harvested product. van Beveren et al.[153] expanded this process further by including a dynamic CO_2 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_2 concentration, the maximum amount of CO_2 available, and the effect of different bounds on optimal energy input. The addition of the dynamic CO_2 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_2, which occurs in a greenhouse with active cooling. Nadal et al.[154] presented an energy and environmental assessment for a roof-top greenhouse and showed that their greenhouse achieved an annual saving in CO_2 emissions of 113.8 kg/m^2 per year, relative to an equivalent oil-heated greenhouse. Vadiee and Martin[155] 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[156] has concluded that evapotranspiration has a significant impact on the micro-climate[156,157]. 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[142] and solar energy conservation[141] to reduce fuel consumption[158]. 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[120]. 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[124]. 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[144, 159-162] and will be less dependent on higher-cost cooling methods such as evaporative[67,163-167] and high pressure fogging systems[168]. 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[165]. 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

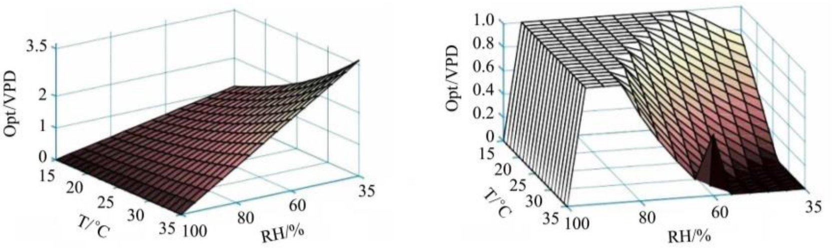
Greenhouse growers use prediction tools for the weather forecast, photosynthesis predictions for plant growth progress[170], predicting disease[171], simulation of yield[172], and production planning and cost-benefit analysis. Some of the earlier examples of climate models to predict the temperature 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[75]. 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[176,182]. 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.[78] This model was used by Graamans et al.[183] 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.[184] 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[185], TOMPOUSSE[186,187] and TOMGRO[188,189]. 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[189] 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[188] and the third version[190], 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, mmol/(m^2 s), air temperature, ℃ and CO_2 concentration, ppm. A simplified version of TOMGRO[189] 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.[189] 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 CO_2 concentration were not included in this version. In addition, Jones et al.[189] 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.[193] evaluated and verified the performance of the reduced state variable version of TOMGRO model of Jones et al.[189] 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.[193] 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.[193] 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].

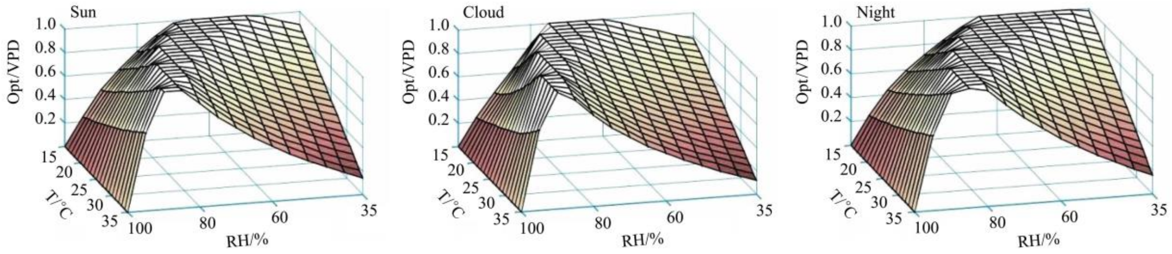
4.4 Decision support systems

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[195], the culture period and practice such as seedling production[196], event-based irrigation[197] and the control and management of environment based growth models[198]. 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.[199], Clarke et al.[195] and Sun et al.[200]. A DSS was built by Tchamitchian et al.[201] 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.[203] and Aiello et al.[204]

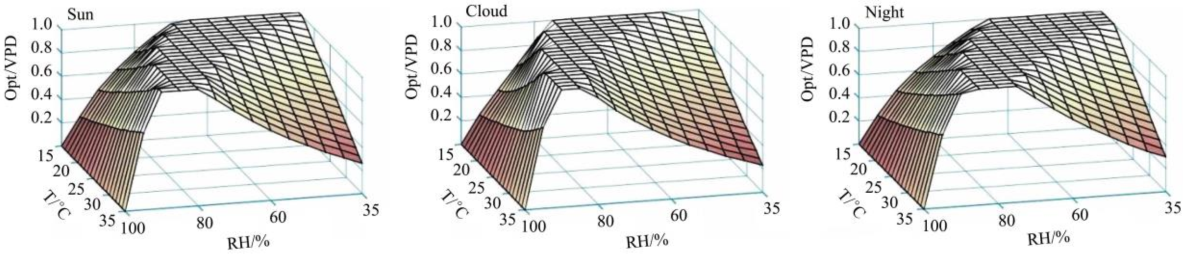
An interactive decision support system (DSS) developed by Short et al.[205] based on the HYTODMOD growth response model of El-Attal[206] is available to describe the optimality degrees of air temperature and relative humidity at five growth stages and under three light conditions (night, sun and cloud). These functions were tested and validated by four independent expert growers and were results of experiments with tomato cultivar “Carusso” in an A-Shade greenhouse located at the Ohio Agriculture Research and Development Center with a floor area of 7.3 m^2. 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.[207] integrated the growth response model of El-Attal[206] 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.[120] 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[208], measuring optimality degrees[46], and comparative evaluation of microclimate parameters[193] 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.[120] 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.



a. VPD vs. T and RH b. Opt (VPD) at early growth (all light)



c. Opt (VPD) at vegetative growth stage



d. Opt (VPD) at flowering stage until fruit harvesting

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)

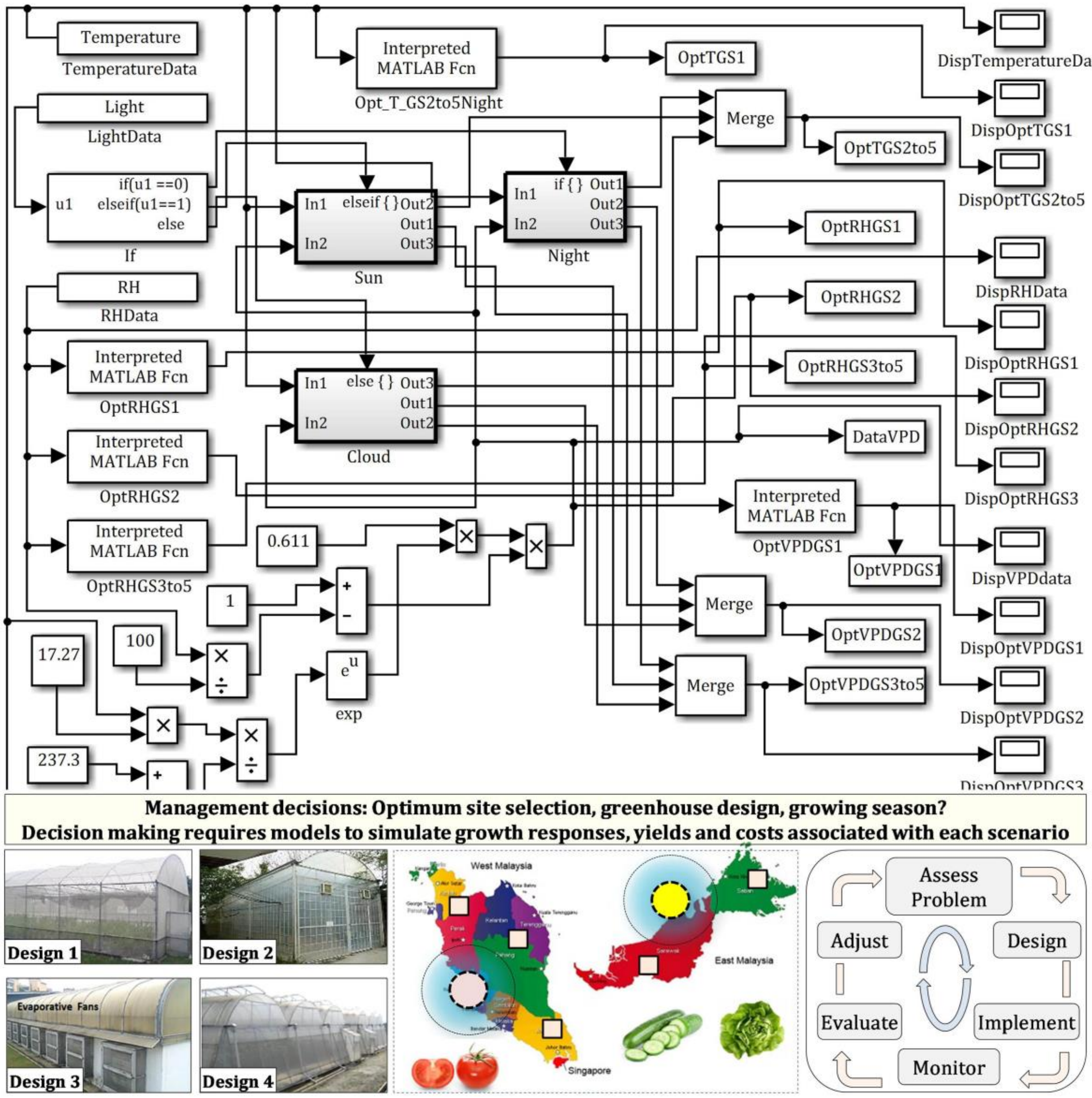


Figure 7 Snapshot of the OptVPD sub-model, a part of the DSS based on adaptive management framework architecture for maximizing tomato yield[120]

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[209] 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[210].

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)[211], integrated farming inside buildings[212], and Z-farming (which stands for ZeroAcreageFarming)[213]. 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[214,215]. "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"[216-219]. 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

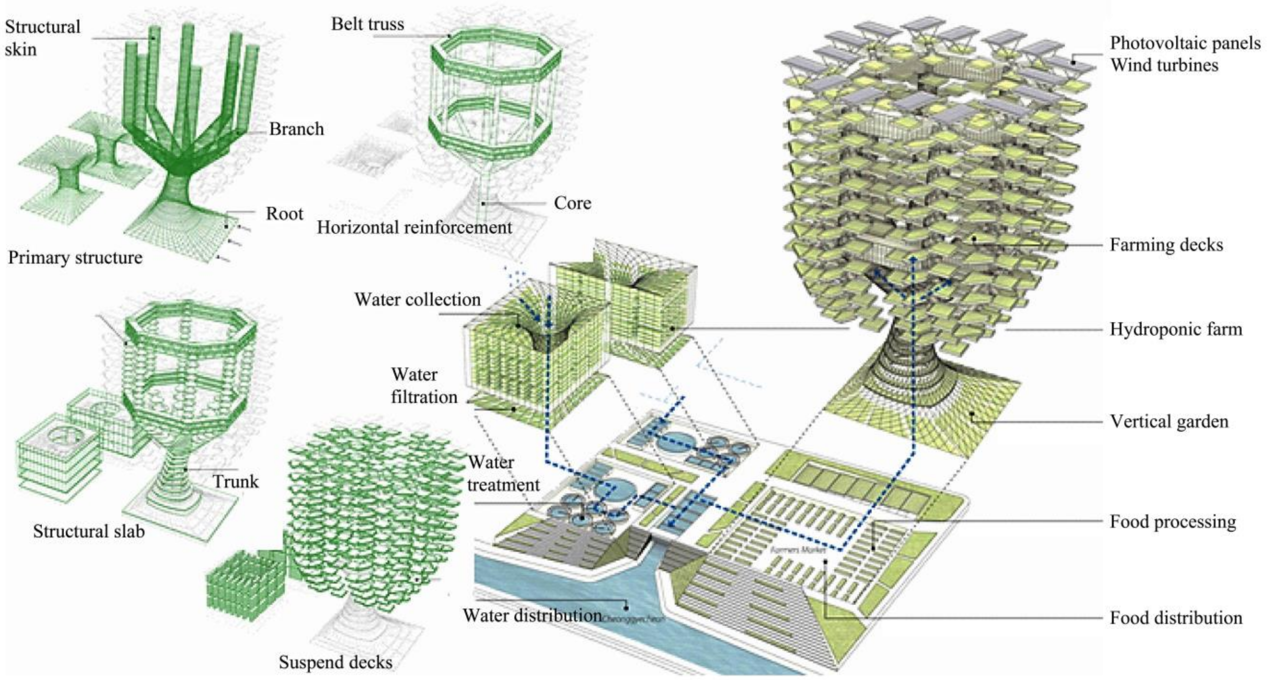
5.1 Vertical farming and rooftop greenhouses

The concept of VF is not new. Kaplan[220] 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”[221]. Designers and landscape architects have frequently looked into the concept, particularly at the end of the 20th 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[222,223]. 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[210,213,224-227].

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.[228] studied the viability of smart technology used in agriculture as an opportunity to be used for VF[228,229]. 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[229]. 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[219,230]. 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.[231] 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.[231] 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[228].

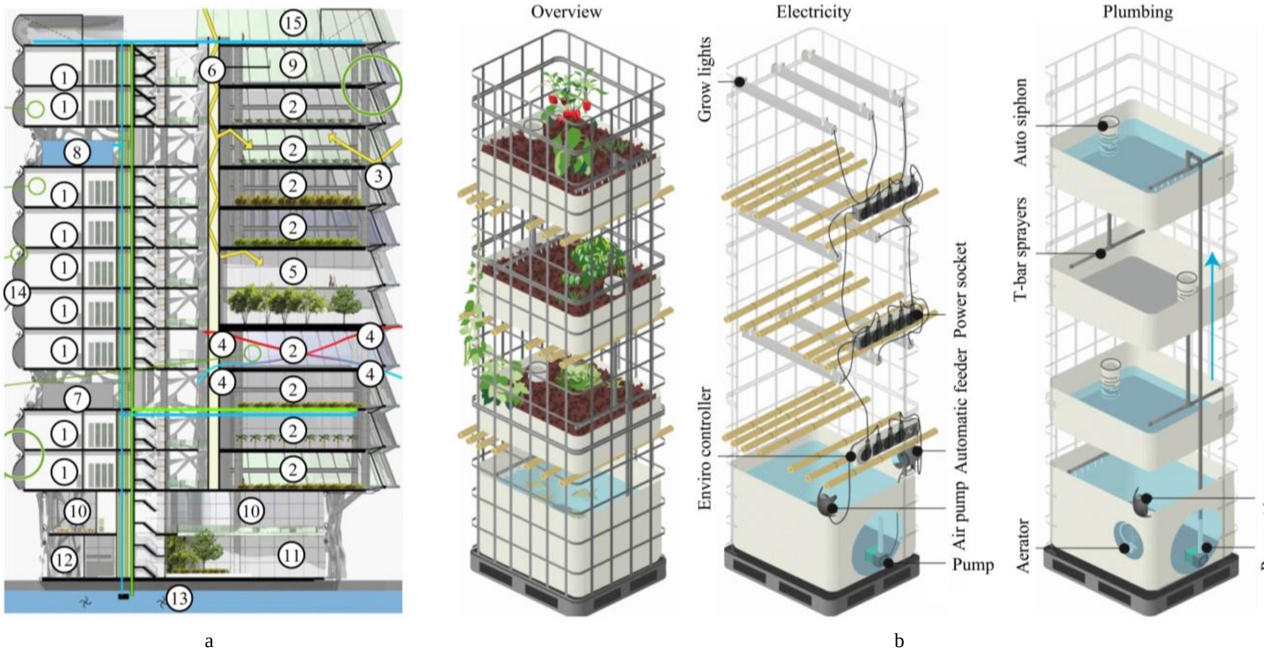
Vertical farms can be diverse from city to city and their structures also vary around the world[210]. The other two conceptual designs for vertical farms are shown in Figure 10. The first design (Figure 10a) was designed by ODESIGN group for Australia. The other type of VF called urban farming units (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[232]. 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[233]. Several advantages of these structure have been reviewed by Pons et al.[234] and Sanyé-Mengual et al.[235], 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_2 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[236], 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.[231])

Company name	Location	Area	Typology of VF	Type of Building	Growing plants	Year	Company website
The Plant Vertical Farm	Chicago, IL	100 000 ft^2	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^2	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^2	3 multi-story with Stacked Bed design	NC	Leafy green vegetables with corn and wheat	2011	cityfarmer.info
Gotham Greens	Brooklyn, USA	1400 m^2	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^2	One floor with Stacked Bed design	NC	Lettuce	2015	miraigroup.jp
Nuvege plant factory	Japan (Kyoto)	30 000 ft^2	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^2	3 multi-floor with Stacked Bed design	NC	Tomatoes, strawberries, lettuce, and micro greens	2012	verticalharvestjackson.com
Planned Vertical Farm	Linkoping, Sweden	-	17 multi-floor	NC	Asian leafy green vegetables	2012	plantagon.com
Green Sense Farms	Portage, Indiana Shenzhen, China	20 000 ft^2	Stacked Bed design	NC	Micro Greens, Baby Greens, Herbs, Lettuces	2014 2016	greensensefarms.com
Aero Farms	Newark, New Jersey	20 000 ft^2	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^2	One floor with Stacked Bed design	RTCB	Tomatoes, lettuce, Spinach, Spinach, Arugula and Kale		brightfarms.com
Lufa Farms Lavel Ahuntsic	Montreal, Canad	43 000 ft^2 32 000 ft^2	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^2	One floor with Stacked Bed design	SC	Lettuces, herbs, and hearty greens	2010	freightfarms.com

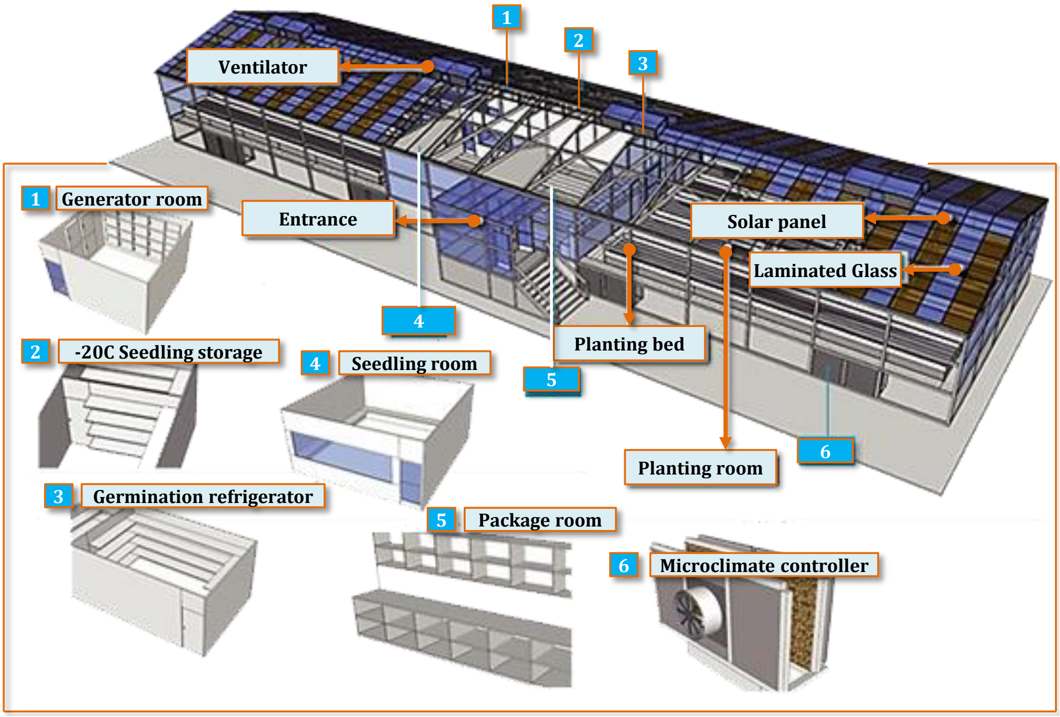
Note: NC: New construction; RTCB: Rooftops of commercial building; SC: Shipping container; GnF: Ground floor; UEB: Underground of existing building.

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[237]. 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[209]. 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[14,238].

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.[239] showed that synergistic effects of monochromic LED together with high CO_2 and nutrients can enhance lettuce growth in a plant factory. Shimokawa et al.[240] 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 ways, i.e., (i) by combination of plant nutrients or phytohormones that is absorbed by plants, (ii) through the movement of soil enhancing nutrient uptake, (iii) protection of plants in stressful circumstances, and consequently cancelling out the negative effects of stress, and (iv) resistance against plant pathogens, reduction of plant diseases or mortalities[241].



Source: Adapted from http://www.richfarm.com.tw.

Figure 11 General structure design of a plant factory

5.3 Opportunities and challenges

Vertical farming entails producing plants in a soil-less culture with nutrient solution and deals with problems concerning the use of soils, including the need for herbicides, pesticides, and fertilizers and then it supplies healthy organic food which is free from chemicals[213]. Another privilege is to remove transportation costs and CO_2 production which accompany the carry-over of foods far away to somewhere near the consumer. Moreover, products can be provided all-year-round corresponding to people's demand. Furthermore, plant-production conditions can be improved to increase the yield by adjusting temperature, humidity, and lighting conditions precisely. Indoor agriculture in a controlled setting also needs much less water than outdoor farming as it involves recycling the graywater and lowering the evaporation. Together with the regulation of temperature and humidity, it can also decrease or omit the effects of seasonality. Freshwater is increased through the evaporation of black and graywater in order to preserve water resources. Moreover, recycled water obtained from rain can be innovatively reused. Recycling and dehumidifying strategies can be used for the city's water supplies. Similarly, aeroponic and hydroponic systems can help raise the efficiency of water consumption to 97% in comparison to traditional agriculture[242]. Moreover, a constant flow of air is produced through air conditioning that can be enhanced with carbon dioxide (CO_2) so as to contribute to plant growth even more. Both environmental parameters and nutrient uptake may be kept at certain levels that improve the speed of plant growth. It was mentioned that plants will have a better evapotranspiration and yield with the modification of bandwidth of LED lighting.

UA, VF, RTG and plant factories provide a unique opportunity for reducing fossil fuels by utilizing solar panels, roof-top wind turbines, or storage batteries[242,243] as shown schematically in Figure 12. The economic benefits of vertical farms include the reduction of the cost of energy, lowering of food price, and an economic opportunity to secure land and return investments to the investor through protecting floods, droughts, or damage caused by the sun. New job opportunities can be created by VF in engineering, biochemistry, biotechnology, construction, maintenance and research, with the chances to improve the technology. Moreover, the social benefits of VF are diverse and involve the psychological, and spiritual health of the community, such as education, leisure, and more social communication and healthier food habits[213,242,244].

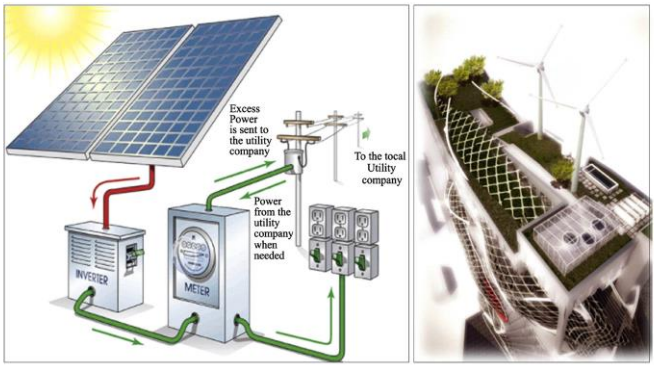


Figure 12 Conceptual design for adaptation of renewable energy for commercial development of sustainable CEA and plant factories

Several researchers have claimed that, in a VF system, the plants on the upper sections of the structure will only benefit from solar radiation, and that the energy supplied by the photovoltaics solar panel may be restricted, or not justified cost wise[225]. However, solar panels are now more efficient in generating energy, 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[229,242]. 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[210] 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[14], 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[245]. It is concluded by Voss[246] 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 introduces 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.

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