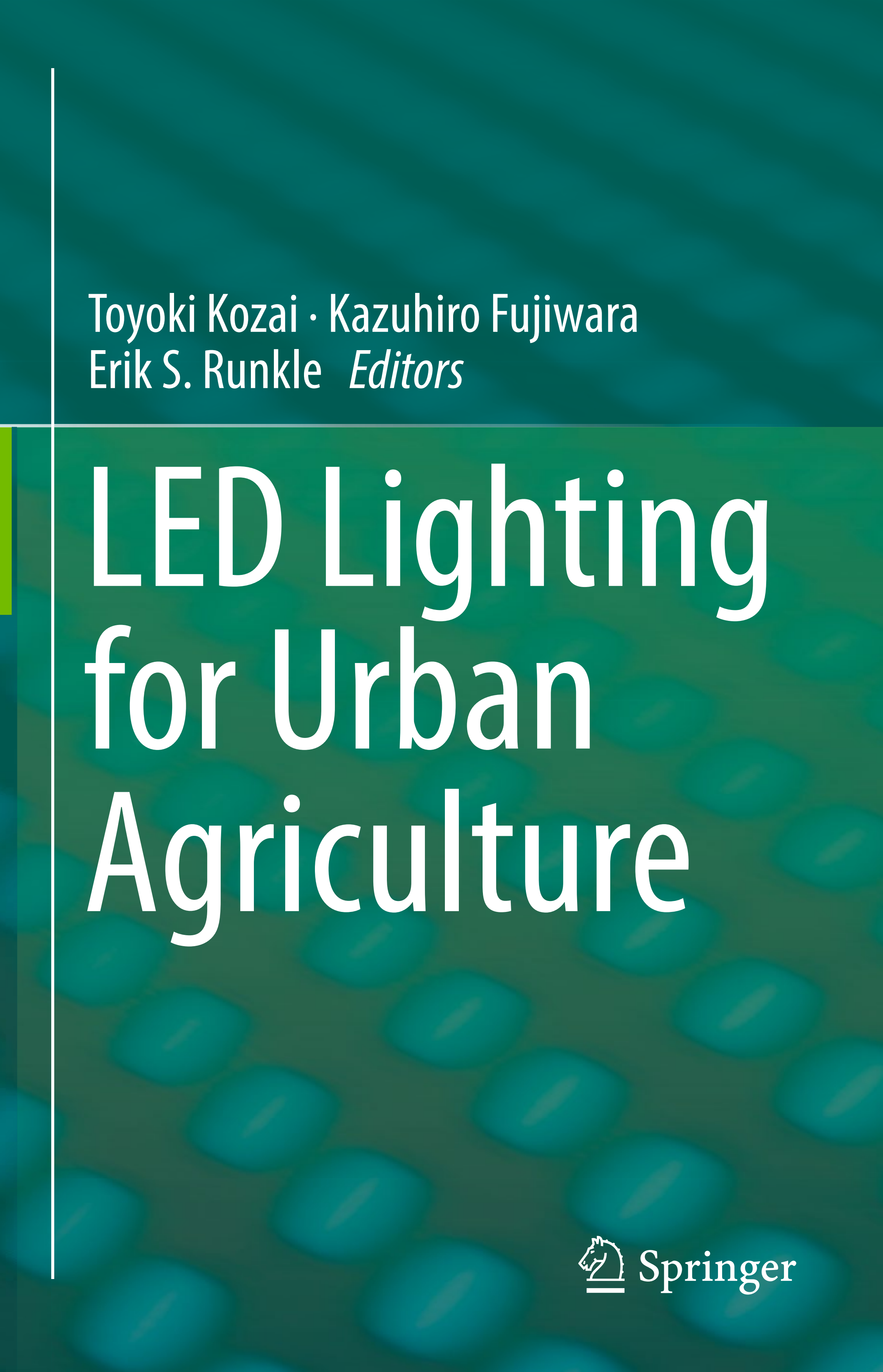

Toyoki Kozai · Kazuhiro Fujiwara
Erik S. Runkle *Editors*

LED Lighting for Urban Agriculture

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Part I
Perspective and Significance of LED Lighting for Urban Agriculture

Chapter 1
Why LED Lighting for Urban Agriculture?

Toyoki Kozai

Abstract The benefits of using light-emitting diodes (LEDs) in urban agriculture are discussed, along with the necessity of introducing information and communication technology (ICT). The incorporation of ICT into urban agriculture is now economically viable because the marginal costs of information processing, storage, and transfer are approaching zero. Electricity generated from renewable resources such as solar energy and biomass is also becoming cost-competitive with that generated from fossil fuel and nuclear power. Internet-connected plant factories lit with LEDs and greenhouses with LED supplemental lighting will serve as key components in urban agriculture. The potential for combined applications of ICT, artificial intelligence, and the Internet of Things in urban agriculture is described briefly. Finally, the concept of closed plant production system (CPPS) and its application in plant factory with LED lighting are described.

Keywords Controlled-environment agriculture • Greenhouse • Light-emitting diode (LED) • Plant factory with artificial lighting (PFAL) • Supplemental lighting • Urban agriculture

1.1 Introduction

Since 2007, more than half of world population are living in urban areas, and it is estimated that over 70 % of world population would live there in 2050. Then, more and more people have recently been interested in urban agriculture or vertical farming (Despommier 2010). Indoor urban agriculture includes atriums, potted plants and plant stands to create green interiors with or without supplemental artificial light, and plant factories with artificial lighting (PFALs) (Kozai et al. 2015). Outdoor urban agriculture includes community gardens (or city farms) in public spaces, home vegetable/flower gardens, orchards, and greenhouses

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with or without supplemental lighting. Issues on PFALs not discussed in this book are mostly discussed in Kozai et al. (2015).

1.1.1 Benefits of Urban Agriculture

Urban agriculture has two basic functions. One is to allow individuals to enjoy environmental horticulture as a hobby, and the other is to produce food and ornamental plants locally for sale to nearby residents. Food and ornamental plant production for local consumption can (1) save fossil fuel, labor time, and packaging material and thus transportation costs; (2) reduce postharvest losses due to damage during transport; (3) increase job opportunities, which benefits those living in urban areas; and (4) allow residents to enjoy a greater variety of fresh fruit and vegetables. By consuming locally-produced fresh food with minimum loss of quality and quantity, urban dwellers also use less electricity and/or fuel for shopping, processing, and cooking.

Since land prices in urban areas are high, the annual productivity of crops for sale per unit of land area must be considerably higher in PFALs and greenhouses than that in open fields. The annual productivity of leaf lettuce plants per unit land area is about 200-fold higher in PFALs and approximately tenfold higher in controlled-environment greenhouses compared with that in open fields (Kozai et al. 2015). If the soil is not sufficiently fertile to grow plants and/or is contaminated with toxic chemicals, heavy metals, etc., hydroponic systems with artificial substrates can be utilized which are isolated from the ground soil.

1.1.2 Benefits of Using Light-Emitting Diodes

Light-emitting diodes (LEDs) are increasingly common in numerous fields due to their good cost performance, relatively high electricity-to-light energy conversion factor, varied coloration (spectra), relatively low surface temperature, long lifetime, solid-state construction without gas, etc. Luminous efficacy (lumen per watt) of white LED tips was 75 in 2010, is 150 in 2016, and will reach around 200 in 2020 (Fig. 1.1). Recent improvement in the luminous efficiency of organic LEDs has also been significant.

Applications of LEDs for horticultural research have been conducted intensively since the 1990s (Massa and Norrie 2015). Fluorescent lamps in PFALs have gradually been replaced by LEDs after the first LED-lit PFAL was built in 2005 for the commercial production of leafy greens. As of 2015, more than 10 of about 200 Japanese PFALs in operation relied on LEDs. While supplemental lighting for greenhouse crops with high-pressure sodium (HPS) lamps has remained popular mainly in the Netherlands and the northern USA since the 1990s (Lopez and Runkle 2016), the HPS lamp versions are also now being replaced by LEDs.

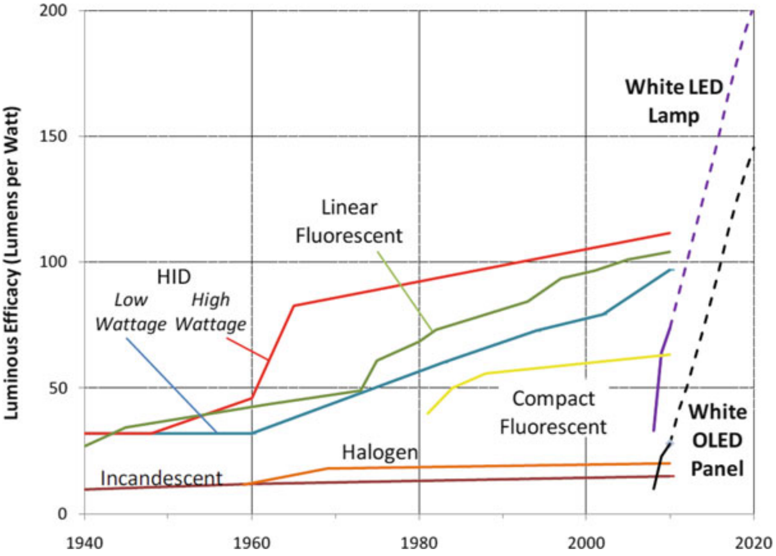


Fig. 1.1 Historical and predicted luminous efficacy of light sources (US Department of Energy 2011)

Plant growth and development are affected by the ambient light, including photosynthetic photon flux density (PPFD, sometimes called light intensity), cycle (light/dark period), ratio of diffuse to direct PPFD, angle determined by geometrical position or solar altitude and azimuth, and quality (wavelength or spectral distribution).

Plant morphology (flower bud initiation, internode length, branching, rooting, etc.) and secondary metabolite production (pigments, vitamins, etc.) are affected significantly by light quality and cycle. Therefore, LEDs with varying light qualities can be used to control morphogenesis and secondary metabolite production more efficiently, increasing the value of crops (see Parts 2 and 5 in this volume).

1.2 Scope of this Publication

This book focuses on LED lighting, mainly for the commercial production of horticultural crops in PFALs and greenhouses with controlled environments, with special attention to (1) plant growth and development as affected by light environment and (2) business and technological opportunities and challenges with regard to LEDs (Fig. 1.2). It contains 31 chapters grouped into seven parts: (1) overview of controlled-environment agriculture and its significance, (2) the effects of ambient light on plant growth and development, (3) optical and physiological characteristics of plant leaves and canopies, (4) greenhouse crop production with supplemental LED lighting, (5) effects of light quality on plant physiology and morphology, (6) current status of commercial plant factories under LED lighting, and (7) basics

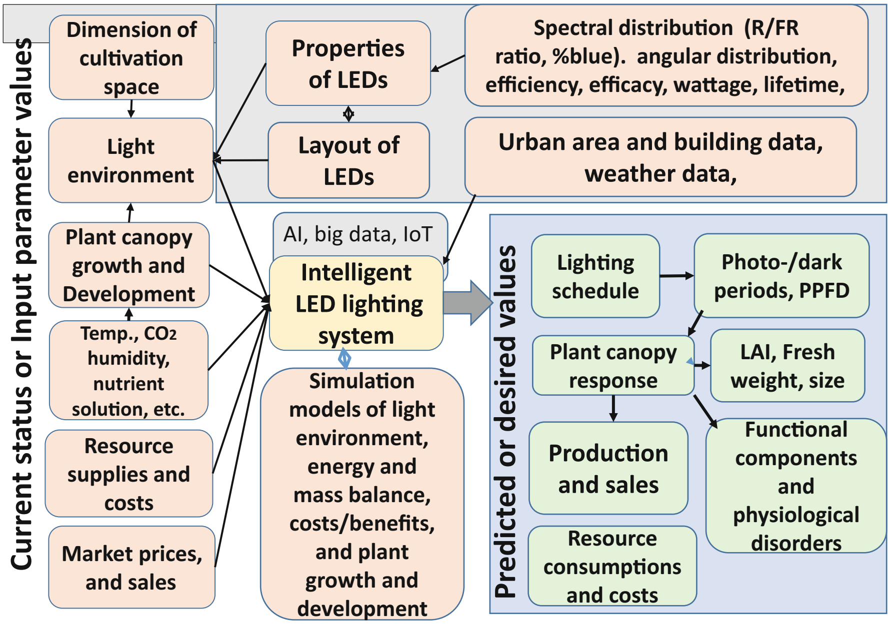
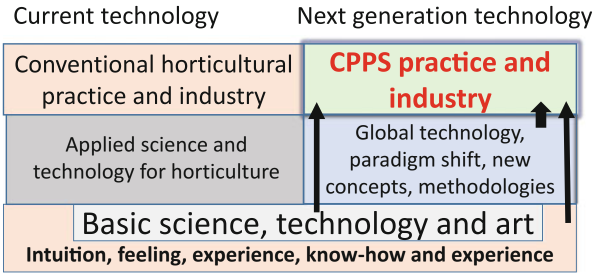


Fig. 1.2 Scientific, technological, and business key components and their structure of LED lighting for urban agriculture



Note: CPPS denotes Closed Plant Production System (see the text for its definition)

Fig. 1.3 A scheme showing that closed plant production system (CPPS) as a major part of urban agriculture in the forthcoming decades will be largely dependent on a new paradigm, concepts, and methodologies, which are not directly related to conventional greenhouse horticulture

of LEDs and LED lighting for plant cultivation. Broader aspects of PFALs, excluding LED lighting, are described in Kozai et al. (2015).

It should be noted that “LED lighting for urban agriculture” in the forthcoming decades will not be just an advanced form of current urban agriculture. It will be largely based on two fields: One is a new paradigm and rapidly advancing new concepts, global technologies on LED, ICT, renewable energy, etc. and methodologies (Fig. 1.3); the other one is basic science and technology which should not be changed for the next several decades. Then, we need to forget about conventional horticultural technology once and to start thinking about the forthcoming urban agriculture based on the abovementioned two fields.

1.3 Technological Background to the Urban Agriculture of the Future

This section describes the technological background to the forms of urban agriculture expected to become widespread in the future. It should be noted that the marginal costs of information processing, storage, and transfer are now approaching zero, as are those of plant DNA genome sequencing (Rifkin 2015). Current fee rates for electricity generated from renewable energy sources are competitive with those generated by fossil fuel and nuclear power. These cost reductions will enable the development of sustainable, economically viable plant production systems with high yields and quality using minimal resources.

1.3.1 Local and Global Technology

Technology can be roughly divided into the local and global types (Fig. 1.4). Many local technologies were originally developed in specific agricultural and/or rural areas, influenced by the climate, soil, water availability, landscape, and other resources. The natural environment and associated agricultural practices then shaped local culture, including festivals, music and dance, cuisine, tools, and social rules. Traditional agriculture was generally sustainable, although not necessarily transferable to other regions.

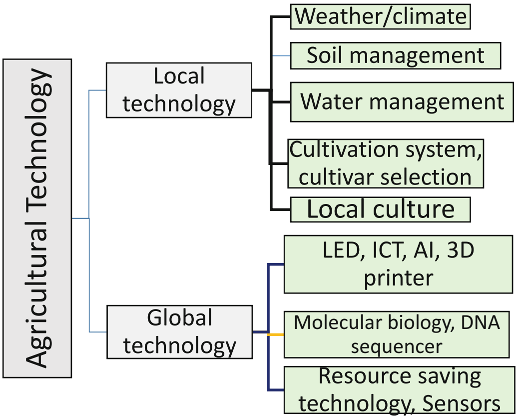


Fig. 1.4 Components of local and global technologies in urban agriculture. *ICT* (information and communication technology), (*AI* (artificial intelligence), *3D* (three dimensional) printer

Global technology, on the other hand, was developed mostly in cities by scientists, engineers, artists, and others, who created what we call "civilization." It sometimes refers to the comfort and convenience of modern life, regarded as available only in towns and cities, as cited in the *Oxford English Dictionary*. Global technology is often universal, expandable, and thus transferable to multiple regions, forming the basis of "Western" science. Typical examples of recent global technologies are computers, the Internet, LEDs, molecular biology-based DNA sequencing, and 3D (three-dimensional) printers.

1.3.2 Introducing Global Technology Locally

While ICT is a global technology, it can be customized by downloading application software, often free of charge, via the Internet and then adjusting the parameters for personal use or by a local or multinational group. It can also be used anywhere, anytime, by anyone at minimum cost. With the application of such global technologies, a sustainable plant production system can be developed as a form of "local culture" that relies on the available natural and human resources.

Any such system must be economically feasible, i.e., resulting in the maximum production of the highest-quality plants with the least possible yield variation, using minimum resources but with the highest use efficiency, and with the lowest cost and pollutant emission. Human welfare and global as well as local sustainability depend on these feasibility considerations.

Along with rapid advances in ICT, other new technology trends are being adopted in many industries (Fig. 1.5) which will affect agriculture in the near future. When local industries introduce global technology to enrich local resources, the advantage of scale enjoyed by large production units tends to decrease.

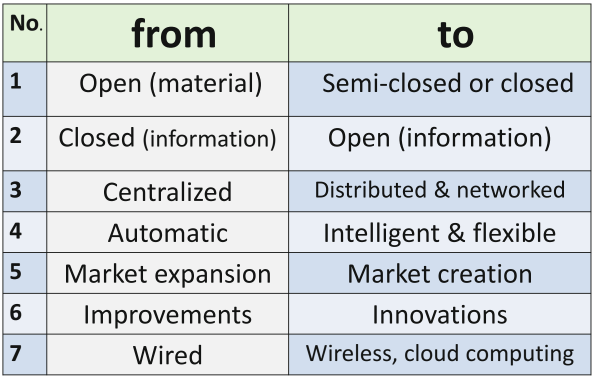


Fig. 1.5 Technological trends in agriculture

No.	from	to
1	Open (material)	Semi-closed or closed
2	Closed (information)	Open (information)
3	Centralized	Distributed & networked
4	Automatic	Intelligent & flexible
5	Market expansion	Market creation
6	Improvements	Innovations
7	Wired	Wireless, cloud computing

1.3.3 Innovative Global Technologies Influencing Next-Generation Urban Agriculture

1.3.3.1 Reductions in the Cost of Information and Bioinformatics

Information processing speeds (million instructions per second per US$1, Mips/US$) of microprocessors increased from 50 in 1990 to 4000 in 2000 and to 7 million in 2010 and will reach more than 100 million in 2015 (Fig. 1.6). In 2015, a micro-SD card measuring 11 mm wide, 15 mm high, and 1 mm thick, weighing only 1 g and priced at US$10, had a 32-GB memory (32 billion bytes; 1 byte is 8 binary digits needed to represent one alphabetic or numeric character), with a data transfer speed of 40 MB/s. Mobile phones had a data transfer speed of 9.6 kilobits per second (kbps) in 1980, which had increased to 100 Mbps in 2015.

Search engines such as Google and Yahoo and a huge number of public databases on genomes, weather, etc. are accessible free of charge. With these advances, computer networks have evolved from large central mainframes with many small terminals into distributed, autonomous, intelligent Internet-based, or networked systems. This change was enabled by steep decreases in the marginal cost of information, i.e., the increase in the total cost for adding one additional unit of new information is approaching zero.

The marginal cost of DNA sequencing is approaching zero even more rapidly than that of microprocessor information. The processing speed of DNA sequencing was 50 Mips/US$ in 2000, 7 million Mips/US$ in 2010, and 1 billion Mips/US$ in 2015 (Fig. 1.7) (Wetterstrand 2011). Fees for analyzing other bioinformatics have

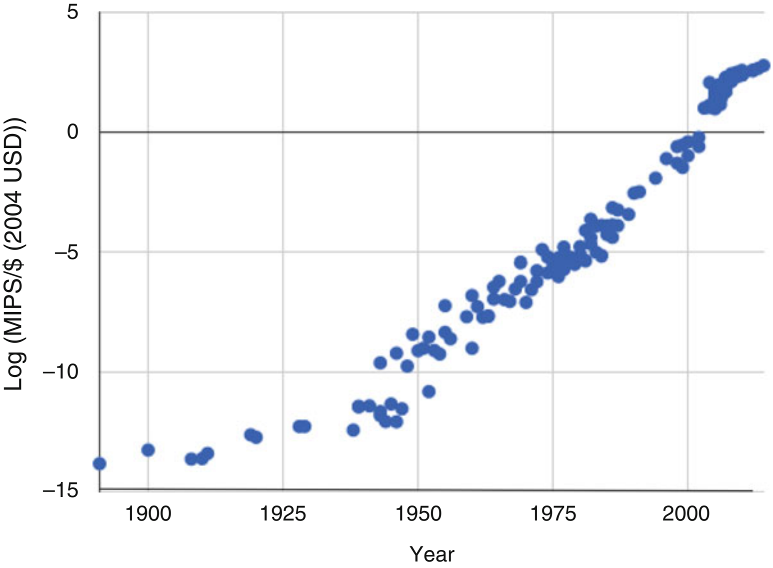


Fig. 1.6 Cost (USD) of microprocessor chip for MIPS (one million floating-point operations per second). (Trends in the cost of computing, 2014), http://aiimpacts.org/trends-in-the-cost-of-computing/

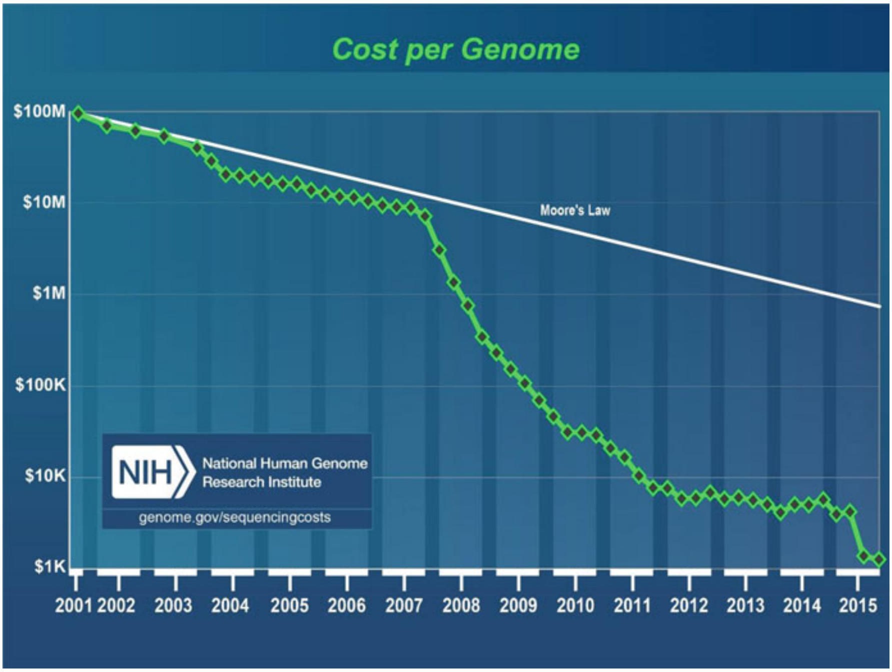


Fig. 1.7 Recent trend in cost of sequencing a human-sized genome. National Human Genome Research Institute (NHGRI) (https://www.genome.gov/images/content/costpermb2015_4.jpg)

also dropped sharply. These have allowed the new research area of "phenomics" to emerge, which involves the measurement and analysis of changes in the physical and biochemical traits of organisms in response to genetic mutations and environmental effects.

1.3.3.2 Levelized Cost of Electricity Generated from Renewable Energy Sources

The levelized cost of electricity (LCOE) is a measure of a power source to compare different methods of generation. It is an economic assessment of the average total cost of building and operating a power-generating asset over its lifetime divided by its total energy output over that lifetime. LCOE in the Organization for Economic Co-operation and Development (OECD) and non-OECD countries is shown in Fig. 1.8 (International Renewable Energy Agency 2015). Although the cost ranges for renewables are wide, reflecting varying resource quality and capital costs, the weighted average LCOE is competitive with new fossil fuel-fired generation options. For example, where oil-fired generation is the predominant power generation source (on islands, off grid, and in certain countries), a lower-cost renewable solution almost always exists today.

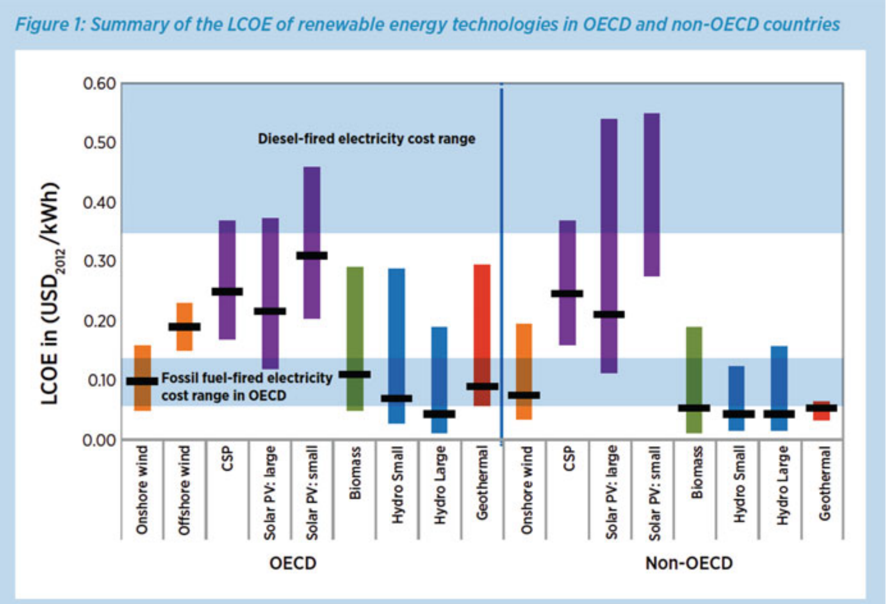


Fig. 1.8 Levelized cost of electricity (LCOE) of renewable energy technologies in the Organization for Economic Co-operation and Development (OECD) and non-OECD countries (2016). International Renewable Energy Agency, http://costing.irena.org/

The competitiveness of renewable power generation technologies continued improving in 2013 and 2014, reaching historic levels. Biomass, hydropower, geothermal, and onshore wind resources can all provide electricity competitively compared with fossil fuel-fired generation. Solar photovoltaic power has also become increasingly competitive, with its LCOE at utility scale falling by one-half in 4 years.

1.3.3.3 3D Printing

A 3D printer is a type of industrial robot, and 3D printing refers to various processes used to synthesize three-dimensional objects made of different kinds of metals, plastics and soils. According to a Wikipedia entry (2016), in 3D printing (https://en.wikipedia.org/wiki/3D_printing#Printers), successive layers of material are formed under computer control to create an object. The object can be of almost any shape or form and is produced from a 3D model or other electronic data sources. It will eventually be possible to send a blueprint of any product to any location place via the Internet for replication on a 3D printer. For example, with a 3D printer installed at home or in a nearby facility, 3D data on an object will be downloadable from the Internet to produce objects or machine parts as needed.

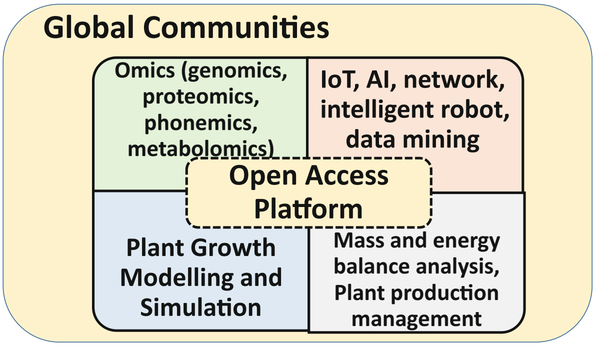


Fig. 1.9 Open-access platform for next-generation urban agriculture

1.4 Next-Generation Urban Agriculture

PFALs and greenhouses with LEDs will play a central role in urban agriculture because of the recent improvements in the electricity-to-light energy conversion factor of LEDs and reductions in the cost of electricity generated by renewable energy sources. Simultaneous decreases in information processing and bioinformatics costs are ushering in a new era of agricultural technology. Big data can be collected using ICT from many PFALs, greenhouses, and other agricultural facilities, while data in open-access databases can be analyzed by cloud computing with artificial intelligence via the Internet at minimal expense (Harper and Siller 2015). Adopting the Internet of Things and 3D printing in urban agriculture will improve the resource use efficiencies of plant production systems and/or food chains in urban areas (see Chap. 3).

On the other hand, in closed or semi-closed plant production systems such as PFALs and greenhouses, ecophysiological modeling and simulation are useful to predict plant growth and development, as well as mass and energy balances in the systems (Takakura and Son 2004; Yabuki 2004). By constructing open-access platforms consisting of databases, knowledge bases, rule bases, search engines, etc., more efficient, sustainable plant production systems are within reach (Fig. 1.9).

1.5 Closed Plant Production System (CPPS) (Kozai 2013; Kozai et al. 2015)

Requirements of a commercial plant production system in urban agriculture include high annual productivity per unit land area, high cost performance, safe and healthy produce, sustainable and stable production, high resource use efficiencies, and economic and social viabilities. The use of LEDs can contribute to meet all of these requirements, especially when used in a closed plant production system (CPPS).

The CPPS concept is relatively well introduced in commercial plant factories with artificial lighting (PFALs), while there exist few commercial “CPPSs with solar light” or “closed greenhouses,” although its research, development, and commercial trial were extensively conducted during 2000–2015 in the Netherlands and other countries (De Gelder et al. 2012).

Difficulties about the commercialization of PFAL and closed greenhouse at that time period were due to its high cost and some technological problems. Even so, potential benefits of PFAL and closed greenhouse with LEDs in urban agriculture are considerable. Thus, understanding the concept, characteristics, and related methodology of CPPS is important when designing and operating PFAL and closed greenhouse with LED lighting.

1.5.1 Concept of CPPS

The CPPS is briefly defined as a plant production system covered with thermally insulated and airtight walls (e.g., Kozai 2013; Kozai et al. 2015). PFAL is one type of CPPS covered with walls which do not transmit solar radiation at all. PFAL consists of six main components: (1) tiers with lamps and hydroponic culture unit, (2) air conditioner, (3) CO_2 supply unit, (4) nutrient solution supply unit, (5) environmental control unit, and (6) thermally insulated and airtight structure to accommodate the abovementioned six units. Closed greenhouse is another type of CPPS covered with walls which transmit a large or small portion of solar radiation and heat energy through plastic or glass walls, with or without thermal/shading screen inside or outside the walls. (Ventilation fans are installed in the CPPSs for emergency use only.)

In both types of CPPS, since air exchanges (or ventilation) are negligibly small, hourly amounts of input material resources (water, CO_2, fertilizer, seeds, etc.) and of electric energy supplied can be measured relatively accurately. Those of output materials (produce, wastewater, plant residue, etc.) can also be measured relatively accurately (Fig. 1.10), while accurate estimation of heat and radiation energy exchanges between inside and outside the closed greenhouse is not so easy.

Chemical energy fixed in whole plants can be estimated relatively accurately based on the fresh weight of whole plants and its averaged percent dry matter. Hourly heat energy removed to the outside by the air conditioner and light energy emitted by the lamps can be estimated accurately in the case of PFALs. In summary, visibility and controllability of the environment and plant growth are highest in PFAL, followed by closed greenhouse, ventilated greenhouse, and open field. More importantly, in the CPPS, we can estimate or measure and control hourly values of “rate variables” (see below) in addition to those of “state variables.”

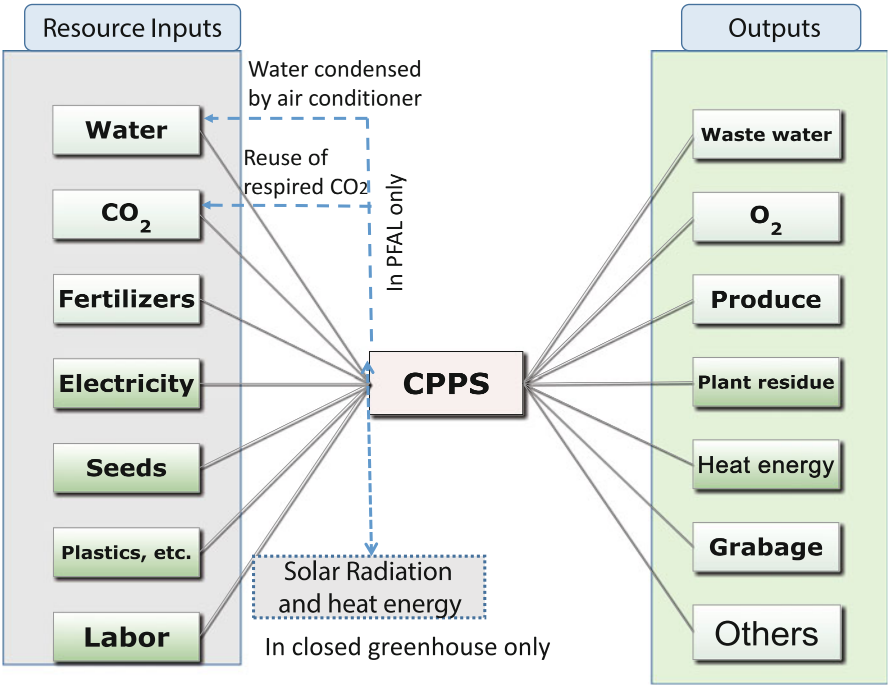


Fig. 1.10 Resource inputs into and outputs from CPPS (PFAL and closed greenhouse)

1.5.2 Estimating Rate Variable Values in the CPPS

Rate variable is a variable with unit of time (e.g., hourly change in weight; kg h^{-1}), while state variable is one without unit of time (e.g., kg). In the CPPS, we can estimate the ecophysiological responses of plants to the environments, such as hourly rates of water uptake, transpiration, net photosynthesis, dark respiration, fertilizer uptake, and hourly or daily rates of fresh weight increase and waste emission.

Uptake rate of each nutrient element can also be estimated by using the measured values of water uptake and concentration of each nutrient element in the culture bed (Kozai 2013). Also, we can measure seed germination rate and yield rate of plants (the weight ratio of salable part of plants to the whole plants) every day.

This advantage of CPPS with the use of measured rate variables will open a new era of plant production system, because hourly measurements of rate variables enable us to estimate resource use efficiencies (RUEs) online. Until now, measured values of state variables such as temperature, CO_2 concentration, water vapor pressure deficit (VPD), pH, and electric conductivity (EC) of nutrient solution only are used to control the environment for plant growth in PFAL and closed greenhouse.

1.5.3 Resource Use Efficiency (RUE) and Cost Performance (CP)

Based on the measured values of rate variables mentioned above, resource use efficiency (RUE, the ratio of resource fixed or held in products or plants to the resource input) in the PFAL can be calculated and visualized on the monitor screen for each resource component hourly, daily, and/or weekly. The RUE includes the use efficiencies of light energy, water, fertilizer, seeds, electricity, etc. Electricity use efficiencies include (1) electricity-to-light energy conversion factor (LEDs generally show higher values than other light sources), (2) conversion factor of light energy to chemical energy fixed in plants, and (3) coefficient of performance (COP) of air conditioners. Seed use efficiency and/or seedling use efficiency is also calculated. In "perfect CPPS," all the resource inputs are converted to the produce with or without plastic bags, so that no environmental pollutants, except for heat energy, are emitted to the outside.

In this way, we can monitor and analyze the RUE for each resource component at an arbitrary time interval, which enables us to improve each RUE and the total performance of PFAL systematically. This feature of PFAL is important for developing a methodology to improve the RUE and cost performance (CP) with low coefficient of variance (CV, ratio of standard deviation to the average) steadily with time. Once the methodology is developed for CPPS, the methodology can be applied for the closed greenhouse, after some modifications, and can also be applied in the ventilated greenhouse.

Cost performance (CP) for each resource input is briefly defined and calculated by the equation

$$\mathrm{CP} = \mathrm{RUE} \times (\mathrm{E}/\mathrm{P})$$

where RUE is the resource use efficiency, E is the economic value per unit weight, and P is the production cost per unit weight. The time span can be hourly, daily, weekly, or monthly. The unit production cost includes the unit cost for processing the environmental pollutants.

Overall economic benefit is expressed as a product of overall CP and a total amount of produce. High CP needs to be associated with high RUE and low CV for sustainable food production. The above equation needs to be generalized for multi-resource inputs in its actual business application.

1.5.4 Rate Variable Control

The yield and quality of a crop cultivar are strongly affected by the changes in rate variables of photosynthesis, dark respiration, transpiration, nutrient uptake, water uptake, translocation, etc. Those rate variables are affected by the environments and ecophysiological characteristics of the crop. In turn, the rate variables affect the environments in the CPPS. These relationships in the CPPS are expressed by simultaneous differential equations.

In the PFAL, we can measure those rate variables relatively easily and also can measure the rate variables of resource inputs such as electricity, water, fertilizer, and CO_2 relatively accurately (Kozai 2013). Then, hourly and daily RUE for each resource element can be estimated relatively easily, while it is difficult and costly to measure such rate variables in the open greenhouse and open field. This is an essentially important point of the plant production in the CPPS.

1.5.5 Current Advantages of PFAL

Even though there exists only one commercial PFAL at Chiba University operated by PlantX Corp. with rate variable measurement control, there are many other advantages of PFAL shown below:

1. *Relative annual productivity* per unit land area is currently 100–200 times higher in the PFAL with high operation skills than in the open fields and 10–20 times higher than in the hydroponic greenhouse. In the case of the PFAL with ten tiers, a typical annual productivity is about 2500 leaf lettuce heads/m^2 (80 g fresh weight per head) or 200 kg/m^2.

This annual productivity being proved by many commercially operated PFALs is mainly due to (1) multilayers (10–15 tiers), (2) plant growth promotion by environmental control, (3) no damage by pest insects and weather, (4) high planting density, and (5) transplanting on the same day as the day of harvest (360 days in cultivation at the same culture space). In addition, wholesale price per kg is about 30 % higher compared with that of greenhouse-grown vegetables, because of its cleanness (See Nos. 2 and 3 below), etc. Plant growth rate can also be promoted or slowed down to meet the variable demands, market prices, and costs with time.

The relative annual productivity per unit land area of PFAL with 15 tiers is expected to increase up to 300 times or higher within 5–10 years by further improving the environmental control method, LED lighting system, production process management, hydroponic culture system, and other factors which will be described in the following section.

2. *Pesticide-, pest insect-, and foreign substance-free* are important characteristics of PFAL-grown leaf vegetables such as lettuce and spinach. Because of this characteristic, there is virtually no need to inspect foreign substances (fine insects, metals, plastic film pieces, etc.) in the vegetables before serving them. Also, PFAL mangers need virtually no knowledge of pathogen-originated disease and pesticides to grow plants in the PFAL.
3. *Colony-forming unit (CFU)* of PFAL-grown leaf vegetables is generally lower than 500, while the CFU of greenhouse-grown leaf vegetables is generally 10,000 or higher. Thus, there is no need to wash before eating the leafy greens

fresh. Then, we can save a large amount of water for washing. In the case of greenhouse- or field-grown vegetables, washing with tap water or water containing hypochlorous acid (HClO) is necessary to keep its salinity, by which water-soluble nutrients such as vitamin are dissolved and lost into water.

4. *Duration of life* of PFAL-grown produce is around twofold compared with that of greenhouse-grown produce when they are purchased at shops and kept in the refrigerator at home. This is mostly because the PFAL-grown leafy greens with CFU lower than 500 are packed in a plastic bag and sealed in the culture room just after harvesting and stored in a precooling room at a temperature of 2–5 °C until shipping. By doing so, we can save loss of vegetables after being purchased. Experimental data under different conditions need to be revealed.
5. *Traceability* from seeding through harvesting to delivery to customers is almost perfect with electronic and digital data. Flows and stocks of all the supplies (consumables) and products, wastes, environmental conditions, and operation hours of workers are recorded electronically, and monitor cameras are working all day.
6. *Higher labor productivity* due to light works under comfortable and safe working conditions (20–25 °C, 70–80 % relative humidity, 50 cm/s air current speed) regardless of weather. Then, labor efficiency is improved.
7. *Nighttime (often surplus) electricity* can be used (at a reduced price in many countries). Electricity cost is affected by lighting schedule under the same electricity consumption in case that the cost per kWh is dependent on the time of day and the season of year.
8. *Resource-saving* characteristics of PFALs, except for considerable electricity consumption, are significant, compared with those in the greenhouse (Kozai 2013). Roughly speaking, the following reductions in resource inputs can be realized compared with those in the open fields: pesticide by 100 %, land area by over 95 %, fertilizer by 50 % (recycling use), labor hour per production by 50 % (small land area), and plant residue by 30 % (less loss of plant parts). Water consumption for hydroponic culture is reduced by over 95 % (recycling use of condensed air at the cooling panels of air conditioners).

1.5.6 Current Disadvantages and Challenges of PFAL

Generally speaking, current technology level is much lower in PFAL industry than in Dutch greenhouse industry. PFAL technology has just been emerging and is still at the initial stage, although technological and business potentials of PFAL are very high. Current problems of PFAL business include (1) high production cost consisting of high initial, electricity, and labor costs due to poor design and management, (2) low quality and yield of produce due to poor environmental control and poor prediction of plant growth, and (3) poor production planning and process management. Also, we still do not know how to use LEDs most efficiently.

It is expected that, by 2020–2025, the production cost will be halved by improving light energy use efficiency and the productivity per floor area will be doubled by better environmental control and optimal selection of cultivars (Kozai et al. 2015). In order to achieve this goal, we need to use the global technology to develop the next-generation LED-lit PFAL with computer software of predictive modeling, simulation, and management of PFAL.

References

De Gelder A, Dieleman JA, Bot GPA, Marcelis LFM (2012) An overview of climate and crop yield in closed greenhouses. J HortScience Biotech 87(3):193–202

Despommier D (2010) The vertical farm: feeding the world in the 21st century. St Martin’s Press, New York, 336 pp

Harper C, Siller M (2015) Open AG: a globally distributed network of food computing. Pervasive Comput 14(4):24–27

International Renewable Energy Agency (2015) Renewable power generation costs in 2014, 162 pp

Kozai T (2013) Resource use efficiency of closed plant production system with artificial light: concept, estimation and application to plant factory. Proc Jpn Acad Ser B 89(10):447–461

Kozai T, Niu G, Takagaki M (eds) (2015) Plant factory: an indoor vertical farming system for efficient quality food production. Academic, London, 423 pp

Lopez RG, Runkle ES (2016) Managing light in controlled-environment agriculture. Meister Media Worldwide, Ohio, USA, (in press)

Massa G, Norrie J (2015) LEDs electrifying horticultural science: proceedings from the 2014 Colloquium and Workshop. HortSci 50(9):1272–1273

Rifkin J (2015) The zero marginal cost society: the internet of things, the collaborative commons, and the eclipse of capitalism. St. Martin’s Griffin, New York, 368 pp

Takakura T, Son JE (2004) Simulation of biological and environmental processes. Kyushu University Press, Fukuoka, 139 pp

US Department of Energy (2011) Solid-state lighting research and development: multi year program plan (Fig. 3.4), 130 pp

Wetterstrand K (2011) DNA sequencing costs: data from the NHGRI (Human Genome Research Institute) large-scale genome sequencing program. http://www.genome.gov/sequencingcosts

Yabuki K (2004) Photosynthetic rate and dynamic environment. Kluwer Academic Publishers, Dordrecht, 126 pp

Chapter 2
Integrated Urban Controlled Environment Agriculture Systems

K.C. Ting, Tao Lin, and Paul C. Davidson

Abstract Controlled environment agriculture (CEA) has evolved from very simple row covers in open fields to highly sophisticated facilities that project an image of factories for producing edible, ornamental, medicinal, or industrial plants. Urban farming activities have been developed and promoted as a part of the infrastructures that support residents' lives in high-population-density cities. Technology-intensive CEA is emerging as a viable form of urban farming. This type of CEA is likely to include engineering and scientific solutions for the production of plants, delivery of environmental parameters, machines for material handling and process control, and information for decision support. Therefore, the deployment of CEA for urban farming requires many components, subsystems, and other external influencing factors to be systematically considered and integrated. This chapter will describe high-tech CEA as a system, provide a systems methodology (i.e., the concept of automation-culture-environment systems or ACESys), propose a decision support platform (i.e., the concurrent science, engineering, and technology or ConSEnT, computational environment), and identify challenges and opportunities in implementing integrated urban controlled environment agriculture systems or IUCEAS.

Keywords Urban agriculture • Controlled environment agriculture • Systems integration • Systems informatics and analytics • Decision support

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2.1 Introduction

Since the beginning of human civilization, protective structures for plant cultivation have been developed with increasing sophistication, ranging from growing plants under simple covers to producing large-quantity and high-quality crops within precisely controlled environments. The analysis, planning, design, construction, management, and operation of high-tech controlled environment agriculture (CEA) for plant production require multidisciplinary expertise. Plant science and engineering technology, as well as their interrelationships, are the foundation for technically workable and economically viable high-tech CEA. Today, there is a wealth of knowledge for designing and managing plant-based engineering systems, i.e., phytomation systems (Ting et al. 2003).

It is commonly known that plants require air, light, water, and nutrients while exposed to appropriate ranges of temperature and relative humidity, to effectively grow and develop. The extent of growth and development varies with different plants when subjected to different combinations of the factors above. Plant scientists have, for many years, investigated the fundamental phenomena of plant physiology, photosynthesis, pathology, etc. Horticulturists have explored ways to cultivate and produce plants to satisfy certain purposes. Engineers have developed methods and equipment to create and deliver growing environment, support structures, material handling devices, and logistics operations to enable plant production at various scales. As mentioned above, these expertise need to be integrated in order to result in functional (and preferably optimized) CEA systems. It is also important to consider social, economic, and surrounding environmental conditions for successful "commercial" scale CEA systems (Nelkin and Caplow 2008; Despommier 2010).

It is predicted that, by 2050, the global population will exceed nine billion people and more than 70 % will live in high-population urban areas (United Nations 2014). Food security, in the context of availability, accessibility, utilization, and stability, is expected to be a daunting challenge, especially for the constant supply of fresh vegetables. Energy security and water security are strongly linked with food security. They have to be addressed in an integrated fashion. Therefore, the nexus of food-energy-water plays a very important role in urban food systems. CEA, especially in the form of plant factories (a.k.a. vertical farming), is well positioned to be part of urban food systems and deserves to be systematically analyzed within that context.

Systems analysis is a methodology that emphasizes the interfaces among the components of a system to investigate how components should work together. It is an important task to determine whether it makes sense to integrate interrelated components to achieve predetermined overall (i.e., system level) goals. The analysis can also help identify ways to resolve the interconnectedness of components and explore ways to improve the overall performance or derive the best system design and operation scenario under various constraints (Ting 1998). Systems analyses have been carried out by CEA researchers and practitioners in various ways. The development of information and computational technologies has brought exciting opportunities for advancing our ability to conduct analyses on CEA systems that are with increasing complexities.

2.2 Recent Evolution of CEA

Figure 2.1 depicts the technological and functional evolution of CEA over the past 50 years. Light, temperature, air relative humidity and composition, plant nutrition, etc. are critical environment and physiology factors that determine the plant productivity and quality. Controlled environment, from protected cultivation and greenhouses to sophisticated, environmentally controlled plant factory, aims to provide extended range of microenvironmental conditions to support plant production either during the times when the natural environments are not conducive to plant growth or throughout the year.

2.2.1 Protected Cultivation

Protected cultivation refers to simple covers over plants in the production fields without advanced environmental control systems. They are normally seen in the forms of anchored plastic mulch, floating mulch, and low tunnels (Baudoin 1999). The purpose of protected cultivation is to improve the plant microenvironment for enhanced crop productivity in open fields. The key benefit of protected cultivation is to provide relatively low-cost crop protection from direct impact by the natural elements, such as frost and freezing. It can also promote water use efficiency and reduce risks of damages from insects, weeds, and other predators. There has been a continuing expansion in crop production areas utilizing protected cultivation, as well as an increase in its application in higher-value vegetable crops and flowers/ ornamental plants (Wittwer and Castilla 1995). The comparative advantages derived from protected cultivation were the driving force for researchers and farmers to explore the technical workability and economic viability of creating and investing in increasingly sophisticated operations, equipment, and facilities for plant production.

2.2.2 Greenhouses

Commercial greenhouses started to emerge when better and larger enclosing structures and more elaborate plant growing configurations and devices were added to the original concept of protected cultivation. The larger structure of greenhouses allows sufficient vertical and horizontal spaces for workers to perform

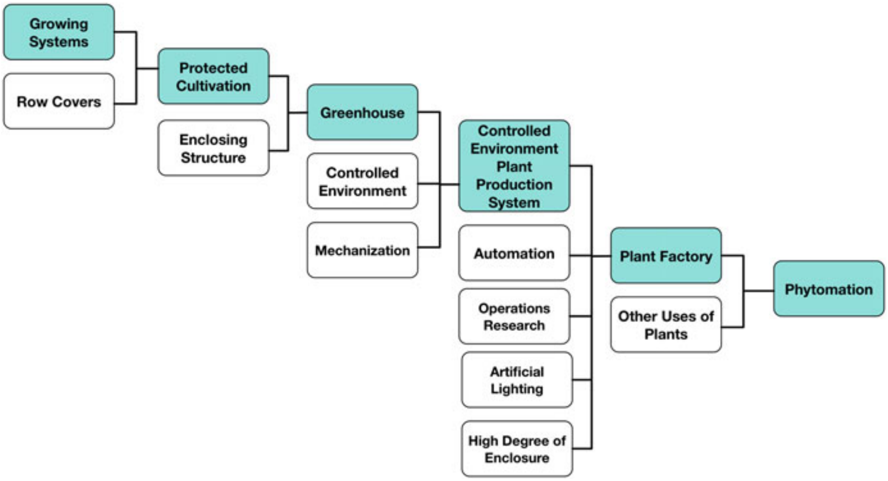

Fig. 2.1 From protected cultivation to phytomation

plant culture tasks and for taller plants to grow upright. The early form of greenhouses had a limited indoor environmental control ability; however, it was capable of providing much better modified environments for plants to produce a profitable yield during unfavorable outdoor conditions. The greenhouse's ability to control the environment under its enclosed structure allowed for an increased productivity of plants and human workers in addition to other direct benefits to plants and workers (Wittwer and Castilla 1995). Many growers started to improve upon the low-cost simple greenhouse structures that had poor environmental control and did not allow plants to reach their potential yield and quality (Baudoin 1999). Heating, cooling, ventilation, lighting, and CO_2 enrichment are key environmental control considerations within a greenhouse. Among them, better temperature controls, especially by heating, were the initial purpose for growers' adoption of greenhouses. The details of functional characteristics and design requirements of greenhouses have been reviewed by von Elsner et al. (2000a, b).

2.2.3 Controlled Environment Plant Production Systems (CEPPS)

Building on the advantages of greenhouses, additional investments were made to add more technologies, including automated indoor environmental control and mechanized plant growing and handling equipment. The impact of the entire production facility to the outdoor environment also started to attract interest. The concept of environmental friendliness of enclosed plant production operations became an important topic in the late 1980s and early 1990s. The increase in complexity of biological, physical, and chemical requirements for efficient plant