

Second Edition



PLANT FACTORY

*An Indoor Vertical Farming System
for Efficient Quality Food Production*



Edited by
Toyoki Kozai, Genhua Niu and Michiko Takagaki



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Preface

It is with great gratitude that we present to you this second edition of *Plant Factory—An Indoor Vertical Farming System for Efficient Quality Food Production*. Our first edition was published in 2015, the very first English book of its kind. We were thrilled when informed by Ms. Nancy Maragioglio, Senior Acquisitions Editor of Elsevier, in late 2017, that sales of our book were strong, and she invited us to prepare a second edition.

Since 2015, significant progress has been made in R&D, industry expansion, and academic research globally in plant factories with artificial lighting (PFALs), owing to the increasing interest and attention to indoor vertical farming and urban agriculture. In this second edition, we have added several new chapters and updated relevant information on existing chapters. The new chapters include Chapter 4, Vertical Farming in Europe: Status and Outlook; and Chapters 9 and 10 on Plant Response to Light and LED Advancement for PFAL, respectively. In Part IV, several chapters have been added to introduce representative PFALs in Japan, the USA, the Netherlands, China, and Taiwan.

It is worth mentioning, as indicated by some reviewers, that this book is a powerhouse for indoor vertical farm. It contains a mixture of information that covers every single facet of indoor vertical farming system, from hardcore science research at post-graduate level, to a general justification of why indoor vertical farming is needed, to examples of commercial operations, and to the status of indoor vertical farms around the globe. Because of the nature of this topic, it is difficult to focus on one single aspect.

We are deeply indebted to all the authors. This book is the product of the contributions of 51 authors. Without their timely contribution, this second edition would not have been possible. We are grateful to Ms. Tokuko Takano for her tireless assistance. We thank Ms. Nancy Maragioglio of Elsevier for inviting us to produce this second edition and Ms. Ruby Smith of Elsevier for her swift responses whenever we had questions and for guiding us to the right answers.

Genhua Niu, Toyoki Kozai, and Michiko Takagaki
April 2019

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Overview and concept
of closed plant
production system
(CPPS)

1

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Introduction

1

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Crop production is increasingly threatened by unusual weather, water shortages, and insufficient available land. The world's population is expected to grow from 7.6 billion in 2018 to 9.3 billion in 2050, and the urban population from 4.1 billion to 6.3 billion. Due to limited natural resources, 90% of the growth in global crop production is expected to be from higher yields and increased cropping intensity, with the remaining 10% from expansion of productive land (FAO, 2009). Almost all of the land expansion in developing countries will take place in sub-Saharan Africa and Latin America. The availability of freshwater resources follows a similar trend, i.e., globally more than sufficient but unevenly distributed. In order to feed the world, protect the environment, improve health, and achieve economic growth, a new form of agricultural cultivation is required: indoor vertical farming using a plant factory system with artificial lighting for efficient production of food crops.

The term “plant factory with artificial lighting” (PFAL) refers to a plant production facility with a thermally insulated and nearly airtight warehouse-like structure (Kozai, 2013). Multiple culture shelves with electric lamps on each shelf are vertically stacked inside. Other necessary equipment and devices for a PFAL are air conditioners, air circulation fans, CO₂ and nutrient solution supply units, and an environmental control unit. Stacking more culture shelves vertically increases the efficiency of land use. Fluorescent lamps (FLs) have been mainly used in PFALs due to their compact size, but light-emitting diode (LED) lamps are now attracting great attention in industry and among researchers. LEDs are increasingly being used in recently built PFALs owing to their compact size, low lamp surface temperature, high light use efficiency, and broad light spectra. More information on the light sources and advantages of LEDs is given in Chapter 8.

PFALs are not a replacement for conventional greenhouses or open-field production. Rather, the rapid development of PFALs has created new markets and business opportunities. PFALs are being used in Japan and other Asian countries for commercial production of leafy greens, herbs, and transplants. Indoor vertical farms, which is another term used in North America for concepts similar to PFALs, are also being built in Europe, the United States and Canada.

When growing plants in an open field, yield and quality are subject to weather conditions, and so a stable and reliable supply of plant-derived food is always in danger. Greenhouse production is not energy efficient because incident light is not regulated. Solar light intensity is often too low at dawn, sunset, and night, on cloudy and rainy days, and throughout the winter season, while it can be too high around noon on sunny days. The temperature and relative humidity inside a greenhouse

are considerably affected by solar light intensity, and thus it is difficult to optimize the environment. In order to lower the temperature, greenhouses are often ventilated, but this allows insects and diseases inside the greenhouse. In addition, CO₂ in a greenhouse with ventilators open cannot be kept higher than outside. Furthermore, light quality and lighting direction are not controllable. Excessive agrochemicals are often used in greenhouse and open-field production and fossil fuels are needed for heating and cooling of greenhouses and for transportation of produce from production site to consumers. Fossil fuels are a nonrenewable energy and excessive use results not only in depletion of resources but also in excessive emission of environmental pollutants including CO₂.

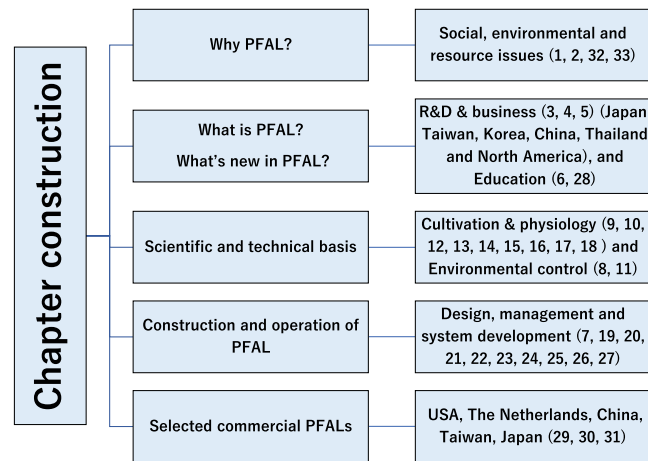
On the other hand, the PFAL is an indoor, advanced, and intensive form of hydroponic production system where the growing environment is optimally controlled. The PFAL is one form of “closed plant production system” (CPPS), where all inputs supplied to the PFAL are fixed by plants with minimum emission to the outside environment. If designed and managed properly, the PFAL has the following potential advantages over the conventional production system:

- a. It can be built anywhere because neither solar light nor soil is needed;
- b. The growing environment is not affected by the outside climate and soil fertility;
- c. Production can be year-round and productivity is over 100 times that of field production;
- d. Produce quality such as concentrations of phytonutrients can be enhanced through manipulation of the growing environment, especially light quality;
- e. Produce is pesticide-free and need not be washed before eating;
- f. Produce has a longer shelf life because the bacterial load is generally less than 300 colony-forming units (CFU) g⁻¹, which is 1/100th to 1/1000th that of field-grown produce;
- g. Energy for transportation can be reduced by building PFALs near urban areas; and
- h. High resource use efficiency (water, CO₂, fertilizer, etc.) can be achieved with minimum emission of pollutants to the outside environment.

Plants suitable for PFALs are those 30 cm or shorter in height such as leafy greens, transplants, and medicinal plants, because the distance between vertical tiers is typically around 40 cm, the optimum height for maximizing the space usage. Also, plants suitable for PFAL should grow well at relatively low light intensity and thrive at a high planting density. Staple food crops consumed mainly for calories such as wheat, rice, and potatoes are not suitable for PFAL production because their economic value per kilogram of dry mass is generally much lower and they require more time to grow than leafy greens.

In addition to commercial production of leafy greens, small PFALs with a floor area of 15–100 m² have been widely used for commercial production of seedlings in Japan because these seedlings can be produced in a short time at a high planting density. Grafted and nongrafted seedlings of tomato, cucumber, eggplant, seedlings of spinach and lettuce for hydroponic culture, and seedlings and cuttings of high-value ornamental plants are produced commercially in these small PFALs in Japan.

There are even smaller PFALs called micro-PFALs or mini-PFALs (m-PFALs), which are described in detail in Chapter 5. These m-PFALs are designed for urban residents who do not have outdoor gardens or for restaurants, cafés, shopping centers, schools, community centers, hospitals, and office buildings. m-PFALs are mainly used for entertainment, as a green interior object, and for the hobby of growing and harvesting plants.

**FIGURE 1.1**

Organization of this book.

Nevertheless, there are a number of challenges or disadvantages to PFALs that must be addressed. Foremost among these are the high initial and production costs. It is estimated that currently the cost of constructing the outer structure is as high as the cost of installing the PFAL units inside (Kozai, 2013). The initial investment can be reduced significantly through better design. The good news is that production costs are decreasing every year as operational and management experience accumulates. Electricity, labor, and materials (seeds, fertilizers, packing, delivery, etc.) account for similar proportions of the production costs. Among the total electricity consumption, lighting accounts for 70%–80%, while air conditioning, pumps, and fans account for the remainder. There is great potential to reduce the cost of lighting by designing a more efficient lighting system. Other approaches to reducing production costs include increasing the number of vertical tiers, shortening the culture period by optimal environmental control, properly designing the production schedule to assure year-round production with no time loss, increasing planting density, and reducing produce losses. Other PFAL challenges include: culture information and an optimal environmental control strategy for various types of crops, marketing of produce, and breeding of new crops suited to PFALs. Chapter 32 describes the challenges and perspectives of PFALs in detail.

This book was written in response to the increasing interest and demand for information on various aspects of PFAL and indoor vertical farming. The book is organized as shown in Fig. 1.1. Historically, there have been several attempts at growing plants indoors using solely artificial light both in Japan and North America. However, these efforts did not lead to successful commercial production mainly because of high equipment and operational costs and fierce competition with conventional production. However, the recent boom in PFALs is different from previous ones and is more realistic. We hope that this book will serve as a source of useful information and provide a vision for PFALs, their diverse opportunities, and the influence on future lifestyles.

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Role of the plant factory with artificial lighting (PFAL) in urban areas

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2.1 Introduction

The increasing importance of fresh food production in urban areas is discussed and the methods for achieving efficient production are described. First, resource inflow and waste outflow in urban areas are described. Then, it is pointed out that a large portion of urban waste can be used as an essential resource for growing plants in urban ecosystems, thus significantly reducing resource inflow and waste outflow. Second, the role of the plant factory with artificial lighting (PFAL, pronounced “P-Fal”) is discussed, and plants that are suited and unsuited to PFALs are described. Finally, criticisms of PFALs are analyzed, and the methodology toward a sustainable PFAL is discussed.

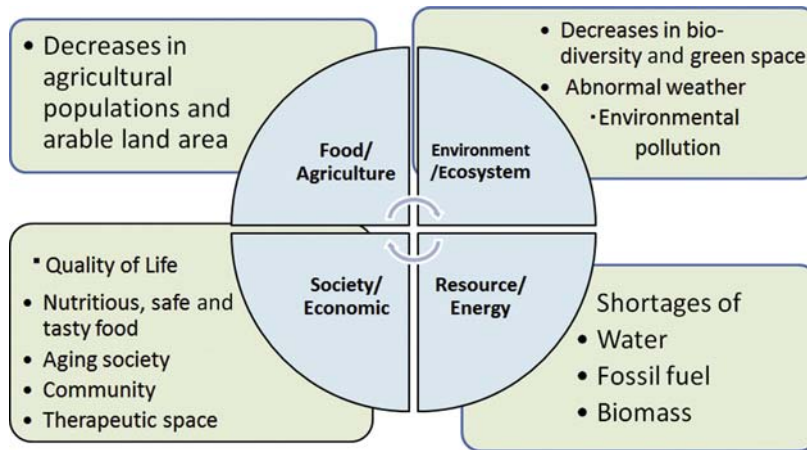
2.2 Interrelated global issues to be solved concurrently

The world is facing interrelated issues concerning agriculture/safe and nutritional foods, the environment, society, and shortages of resources under increasing world population and climate change (Fig. 2.1). Since these four issues are closely interrelated, they must be solved concurrently based on a common concept and methodology (Kozai, 2013a). In other words, we must find a concept and methodology for effectively producing high-quality foods, in order to improve social welfare and quality of life with the minimum consumption of resources and emission of environmental pollutants.

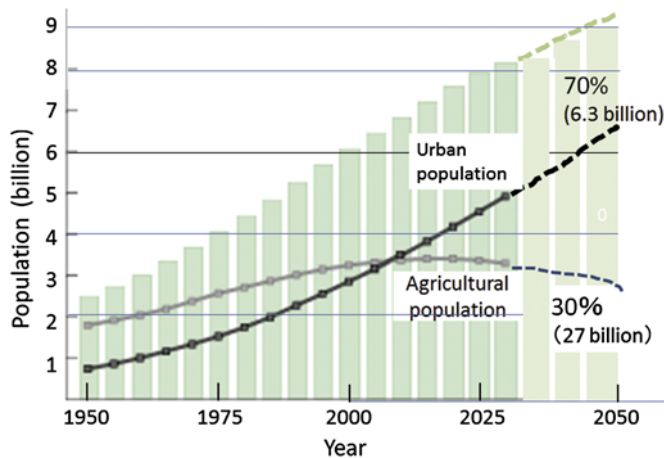
Issues concerning agriculture or food include the dwindling number of farmers due to aging as the urban population increases (Fig. 2.2) and loss of arable land area due to urbanization and desertification, salt accumulation on the soil surface, and soil contamination with toxic substances. The global population is forecast to rise to 9.3 billion people by 2050, 70% of whom will be living in urban areas (UN, 2009, 2017). The urban population in 2050 will require about 70% more food than the 2009 population.

Issues concerning the environment or ecosystem include a decrease in biodiversity and green space, and an increase in environmental pollution and abnormal weather (heavy rain/flood, drought, strong wind, etc., likely due to global warming). These problems often make ecosystems less stable.

The shortage of resources including water, fossil fuels, and phytomass (or plant biomass) is becoming increasingly serious. Large areas for producing staple foods are already facing insufficient

**FIGURE 2.1**

Four interrelated global issues to be solved concurrently for improved sustainability of the Earth and mankind as well as the quality of our lives.

**FIGURE 2.2**

Trends of world, urban, and agricultural populations (cited and extrapolated from [World Population Prospects, 2017](#)).

irrigation water, and drought and/or unstable rainfall, while the demand for domestic water will continue to increase due to expanding urbanization along with the desire for a better quality of life.

Phytomass is becoming an important raw material resource for industrial products as an alternative to fossil fuels, while the reduction in regional phytomass affects the stability of local ecosystems. The shortage of phosphate rock as a raw material for phosphatic fertilizer (PO_4^- , or P), which is an

essential fertilizer in agriculture, will become increasingly serious in the coming decades. On the other hand, excess application of P (phosphate) in crop fields is polluting freshwater rivers and lakes, causing eutrophication (Sharpley et al., 2003).

Issues concerning society and economics include an insufficient supply of nutritious, safe and tasty food, social welfare for building mutually supporting communities, therapeutic space and activities, and systems for education, lifelong self-learning, and human resource development.

The so-called “food deserts” are another related issue that has recently emerged, in which people have no access to fresh vegetables and fruits. Instead, they purchase various processed foods laden with sugar and fat at local convenience stores. Fresh foods produced in urban or suburban areas are transported to food processing factories far from the production site, and some of the processed foods are transported back to the production site. Thus, people living in the production area miss the opportunity to enjoy fresh and healthy vegetables and fruits, while significant resources are used for food processing and transportation.

Despommier (2010) proposed the concept of “vertical farming” to solve the four interrelated global issues, which has had a strong impact on scientists, engineers, policy makers, and architects. Allen (2012) proposed the “good food revolution” for growing healthy food and benefiting people and communities, and started a social business aiming at local production for local consumption of agricultural foods.

Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production describes the technical, engineering, and scientific aspects of “vertical farming” and “local production for local consumption” with a special emphasis on PFAL, an emerging concept and technology.

2.3 Resource inflow and waste outflow in urban areas

Huge amounts of resources are brought into urban areas, and huge amounts of waste are also produced in urban areas. This waste is processed and produced in both urban and suburban areas (Fig. 2.3). The resources include food, water, fossil fuel, electricity, various products, raw materials for industries, and

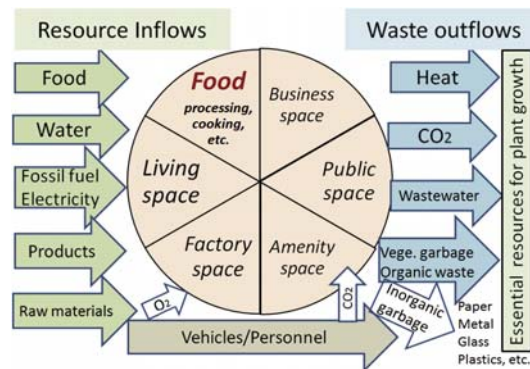


FIGURE 2.3

Resource inflow and waste outflow in urban areas. Most waste produced in urban areas is an essential resource for plant growth by photosynthesis (see also Fig. 2.6).

vehicles. Additionally, large amounts of oxygen gas in the atmosphere are absorbed by humans, animals, microorganisms, and chemical reactions in factories. The waste includes heat, CO₂, wastewater, food garbage, grass clippings, pruned plant branches produced in parks, streets, and gardens, organic solid waste, and inorganic solid waste (plastics, paper, metal, glass, and so forth).

Food is roughly grouped into plant-derived food, animal meat, fish, and mushrooms. It can also be classified into fresh (or raw), frozen, dried, and processed food. Plant-derived food can be classified into functional food (from specialty crops such as vegetables, edible herbs, fruits, and mushrooms), staple food (from commodity crops such as wheat, potatoes, rice, and corn), and confectioneries (such as potato chips, cookies, and pies) (Fig. 2.4). Crops that can be economically and commercially grown for sale in urban areas are basically those used for fresh functional food.

Fresh food with a water content of 90%–95% is heavy and perishable unless cooled or frozen and carefully packaged. In cases where fresh food is transported into urban areas from remote areas by ordinary and small commercial trucks, the CO₂ emission intensity for transportation is, respectively, 0.8 kg and 1.9 kg-CO₂/ton/km (Ohyama et al., 2008). The food in a supermarket in the USA travels about 2000 km on average between its production and consumption sites (Smit and Nasr, 1992). The distance between California (a main lettuce production area) and New York is 4500 km (2800 miles). Additional CO₂ is emitted when the food is cooled during transportation. Thus, transporting perishable fresh food over a long distance to urban areas is resource consuming and environment polluting (Fig. 2.5). On the other hand, if fresh food is not cooled and/or not carefully packaged during long-distance transportation, much of it is lost. Thus, reduction in food mileage or “local production for local consumption” is particularly important in the case of fresh food.

Food garbage and wastewater produced in urban areas must be processed before they are returned to nature or recycled. Considerable amounts of fossil fuel and/or electricity are consumed in this processing. Thus, reducing the resource inflow reduces the waste outflow and CO₂ emissions in urban areas. In other words, the “throughput” of resources in urban areas needs to be reduced (Smit and Nasr, 1992). This can be achieved by changing the current “consume—dispose open loops” into new “consume—process—/recycle/reuse—produce closed loops” with respect to resource input (Fig. 2.6).

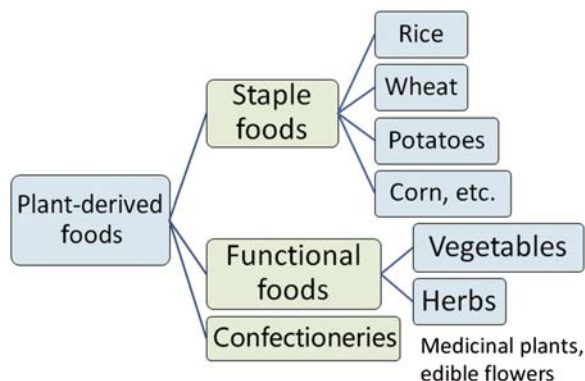
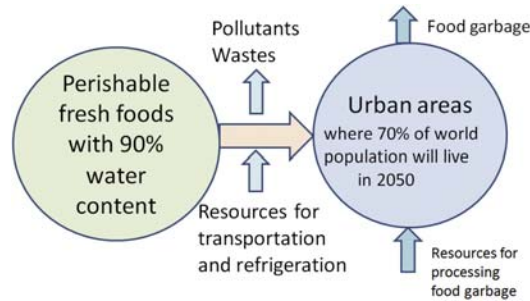
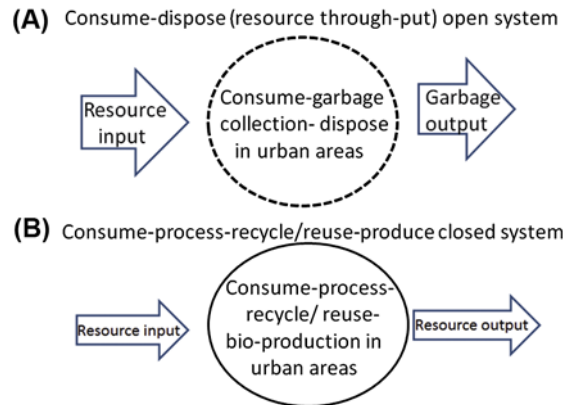


FIGURE 2.4

Classification of plant-derived foods.

**FIGURE 2.5**

Transporting perishable fresh foods over a long distance to urban areas is resource consuming and environment polluting. Furthermore, additional resources are consumed to process the food garbage.

**FIGURE 2.6**

Open and closed urban areas with respect to resource input.

The same concept can be applied to plant production systems, namely, changing from “open plant production systems” to “closed plant production systems,” which are described in Chapter 4.

2.4 Energy and material balance in Urban ecosystems

2.4.1 Photoautotrophs (plants) and heterotrophs (animals and microorganisms)

Plants with green-colored leaves containing chlorophyll require only light, CO_2 , water, and inorganic or mineral elements to produce carbohydrates (primary metabolites) for photosynthesis (Fig. 2.7), and are called “photoautotrophs.” Photoautotrophs synthesize organic compounds such as amino acids, vitamins, proteins, and lipids required for growth and development, using the carbohydrates, minerals, and water absorbed by the roots. Namely, plants do not need organic nutrient elements for their growth,

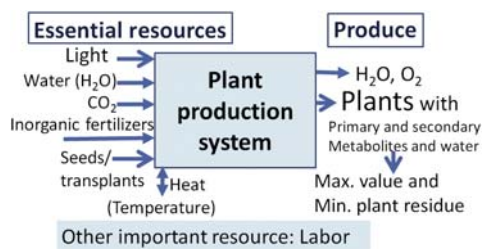


FIGURE 2.7

Essential resources (left) for growing green-colored plants through photosynthesis, and products obtained from plant production system (right).

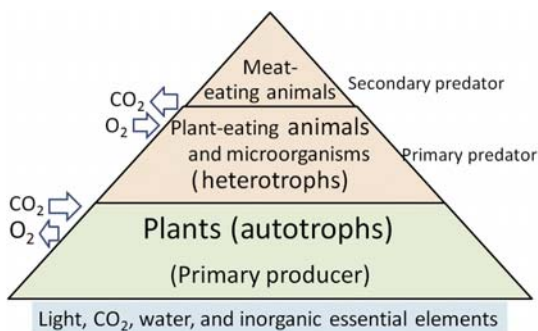


FIGURE 2.8

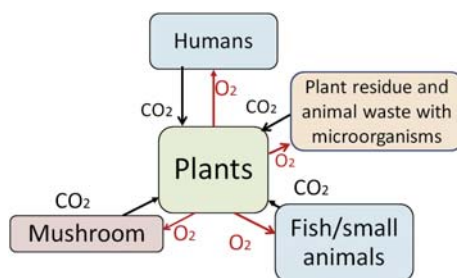
Animals and microorganisms need plants or plant-derived food for growth, so do humans. On the other hand, plants need light, CO_2 , water, and mineral elements only to grow (see also Fig. 2.7).

although the plant roots may take up very small amounts (less than 0.1% of the uptake of inorganic elements) of amino acids, glucose, and others that are present in the soil around the roots.

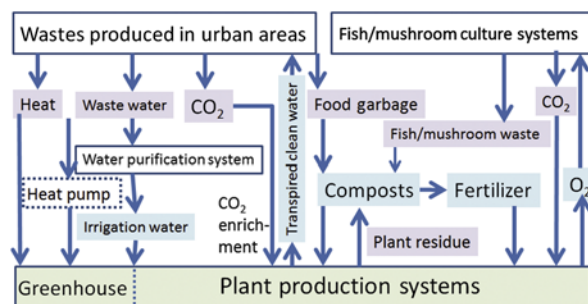
On the other hand, animals and microorganisms require organic elements as essential food for growth, and are called “heterotrophs.” Some heterotrophs must take in certain kinds of inorganic elements such as salts, in addition to organic elements. Some heterotrophs (herbivorous) eat plants as food, while others (carnivorous) eat meat. The rest eat both plants and meat, and/or microorganisms. These nutritional relationships among plants, animals, and microorganisms are often presented as the “food chain pyramid” (Fig. 2.8). In this pyramid, CO_2 and O_2 have a complementary relationship. Namely, photoautotrophs take in CO_2 and produce O_2 , while heterotrophs take in O_2 and produce CO_2 (Fig. 2.9).

2.4.2 Waste produced in urban areas as an essential resource for growing plants

The waste produced in urban areas and fish/mushroom culture systems can be used as an essential resource, after proper processing, for growing plants in urban areas. Fig. 2.10 shows an example of the waste recycle/reuse—bioproduction closed system shown in Fig. 2.6. Technologies have already been

**FIGURE 2.9**

Complementarity of CO₂ and O₂ flows in urban ecosystems.

**FIGURE 2.10**

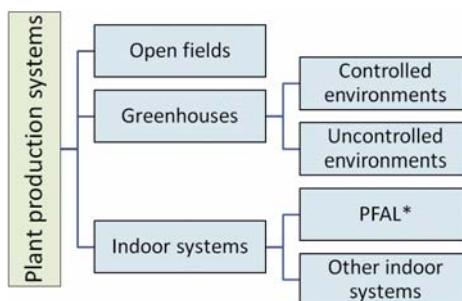
Waste produced in urban areas and fish/mushroom culture systems can be used as essential resources in plant production systems.

developed for the purification of wastewater, production of compost and fertilizer from food garbage and fish/mushroom waste, and collection and distribution of heat energy using heat pumps and/or heat exchangers. It is not difficult to transport CO₂-enriched air produced in offices and factories to nearby plant production systems.

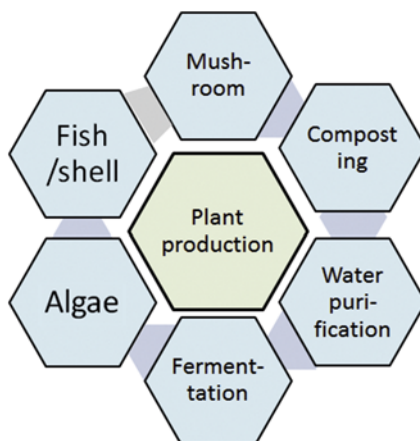
The introduction of various kinds of plant production systems for efficient use of urban waste involves a number of challenges. By using the waste as an essential resource for plant production, the cost of waste processing and of production and transportation of fresh foods can be reduced. Moreover, recycling water, CO₂, heat, food garbage, and other substances in urban areas will enhance the sustainability of food, the environment, society, and resources.

2.4.3 Plant production systems integrated with other biological systems

Plant production systems for fresh foods can be roughly classified into open fields, greenhouses with or without environmental control units, and indoor systems (Fig. 2.11). Some are used for commercial production and others are used for personal, family, and group member activities.

**FIGURE 2.11**

Types of plant production systems. PFAL denotes “plant factory with artificial lighting,” and is precisely defined in Section 2.4.7 of this chapter.

**FIGURE 2.12**

Various biological systems that can be integrated with different plant production systems for reusing waste as a resource in urban areas.

These plant production systems can be integrated with other biological systems (Fig. 2.12). An example of the material and energy flow in those biological systems is shown in Fig. 2.13. By such integration, the amount of waste and environmental pollutants can be further reduced. The amount of resources transported from outside urban areas for producing fresh foods and for processing waste can also be reduced.

Given that the average daily vegetable consumption is about 300 g per person in many countries (FAOSTAT, <http://faostat.fao.org/>, 2009), about 1 million tons [= 0.3 kg (fresh weight)/day/person × 10 million persons × 365 days] of vegetables are consumed per year in a city with a population of 10 million. It is estimated that around 25% of the vegetables purchased in urban areas goes directly into the garbage.

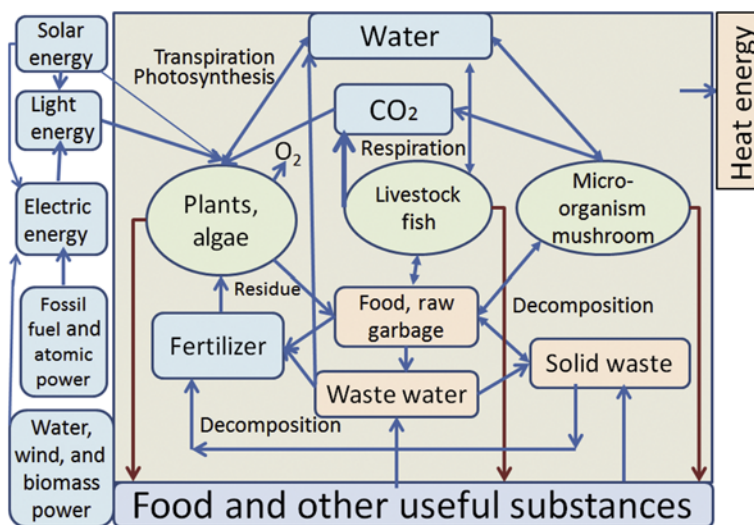


FIGURE 2.13

Material and energy conversion and recycling in urban agriculture.

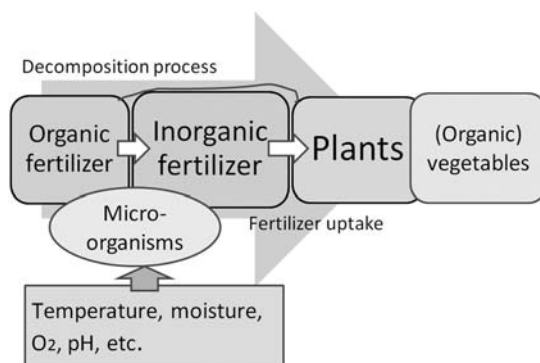
If a significant percentage of the vegetables were to be produced locally, job opportunities would be created and/or citizens could enjoy growing plants and other living organisms such as fish and mushrooms near their residence. Fresh food production in urban areas for local consumption minimizes the food mileage and the loss of fresh food during transportation, and enhances communication among residents. Furthermore, people would understand and experience the principles of circulation of materials and energy in ecosystems. In this way, the four global issues concerning food, the environment, society, and resources can be concurrently solved step by step.

2.4.4 Role of organic fertilizers and microorganisms in the soil

Food garbage, plant residues, fish/animal waste, and other biological waste can be converted into compost or organic fertilizer, or bioenergy (methane gas) for generating electricity. In the future, a system will be developed to extract valuable substances from such waste.

In soil culture in greenhouses and open fields (farmers' fields, community gardens, city farms, and backyard gardens), soil fertility is essential to stabilize the root zone environment and to improve the yield and quality of crops. In general, the application of organic fertilizer improves soil fertility, which can be expressed and evaluated by the chemical, physical, and biological properties of the soil.

The role of organic fertilizer in plant production is indirect. Organic fertilizer is an essential element for the growth of microorganisms in the soil, and is decomposed into inorganic fertilizer as the microorganisms grow. The rate of decomposition of organic fertilizer into inorganic fertilizer is strongly affected by the soil temperature, water content, and pH (degree of acidity) as well as the characteristics of the microorganism ecosystem. This is why the effects of organic fertilizers on the yield and quality may vary. It can take considerable time for organic fertilizer to become effective in

**FIGURE 2.14**

Organic fertilizer is decomposed into inorganic fertilizer by microorganisms, and plants take up inorganic fertilizer mostly, not organic fertilizer. Activities of microorganisms are strongly affected by temperature, moisture, oxygen, pH, and other factors.

the soil and to make the soil fertile with a high degree of stability. In any case, it should be noted that plant roots take up inorganic fertilizer, not organic fertilizer (Fig. 2.14).

Aquaponics, a combination of hydroponics and aqua (fish) culture, is becoming popular in the USA and other countries. In aquaponics, fish waste is decomposed into inorganic fertilizer in the presence of microorganisms (see Figures 5.13 in Chapter 5). An indoor aquaponics farm with a floor area of 4800 m² has been operated by Japan Aquaponics in Abu Dhabi.

2.4.5 Stability and controllability of the environment in plant production systems

Plant production systems can be characterized by their natural and artificial stability, and natural and artificial controllability (Table 2.1). Different plant production systems differing in stability and controllability are needed to maintain the overall sustainability of society under changing climate and social conditions. The plant production system to be chosen depends on its purpose under the given social, environmental, economic, and resource conditions.

In open fields, keeping the soil (root zone) environment naturally stable is of primary importance, because this stability compensates for the low natural and artificial controllability of the aerial environment (weather). The application of organic fertilizer generally enhances the root zone stability with a high buffering function with respect to water content, air porosity, pH, and temperature of the soil, and high population density and diversity of microorganisms (not all kinds of microorganisms are beneficial for plant growth, so it is important to keep the beneficial microorganisms dominant in the soil).

Indoor plant production systems can generally be characterized by their high artificial controllability of both the aerial and root zone environment, or low natural stability and low natural controllability of both the aerial and root zone environment. To keep the artificial stability and controllability at a high level, an intelligent environment controller is necessary to minimize the resource consumption and environmental pollution.

Table 2.1 Classification of four types of plant production systems by their relative stability and controllability, and other factors.

Stability and controllability	Open fields	Greenhouses		Indoor systems ^a
		Soil culture	Hydroponics ^a	
Natural stability of aerial zone	Very low	Low	Low	Low
Artificial controllability of aerial zone	Very low	Medium	Medium	Very high
Natural stability of root zone	High	High	Low	Low
Artificial controllability of root zone	Low	Low	High	High
Vulnerability of yield and quality	High	Medium	Relatively low	Low
Initial investment per unit land area	Low	Medium	Relatively high	Extremely high
Yield	Low	Medium	Relatively high	Extremely high

^aHigh/low evaluation is valid only when the manager's skills are fairly high.

Greenhouses show intermediate stability and controllability between open fields and indoor systems. Soil culture has a higher natural stability than hydroponic cultures with respect to the root zone environment. On the other hand, the soil in urban areas is often contaminated with heavy metals, agrochemicals, and other toxic substances (Garnett, 2001). This problem can be avoided by using a hydroponic greenhouse where the culture beds (root zone) are isolated from the soil.

Salt accumulates on the soil surface in the greenhouse due to excessive application of chemical fertilizer and/or livestock manure for many years, reducing crop yield. This reduction in yield can also be avoided by using the hydroponic culture system.

The high cost of greenhouse heating is a major factor in greenhouse crop production in winter. However, in urban areas, waste heat from industrial factories and offices can be used as a heat source for heating (Figs. 2.3 and 2.13). In a case where the heat source temperature is too low (10–20°C) but the amount is abundant, heat pumps can be efficiently used to raise the waste heat temperature up to 40–60°C for heating.

2.4.6 Key indices for sustainable food production

There are three key indices for evaluating the sustainability of fresh food production systems: (1) resource use efficiency (RUE, the ratio of resource amount fixed by produce to resource input); (2) productivity or cost performance (CP, ratio of sales amount to production cost); and (3) vulnerability (V) or yearly deviation of yield and unit value (quality) (Fig. 2.15 and Chapter 5). Resource input at the system construction stage can be included, if needed, by LCA (life cycle assessment, Chapter 27). In the design and operation of a fresh food production system, its sustainability should be primarily evaluated by these indices.

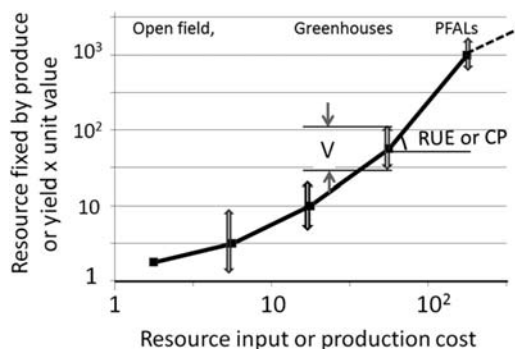


FIGURE 2.15

Scheme showing the (yield $\times$ unit value) and its vulnerability as affected by the amount of resource input. Increases in initial and operation resource input are justified only when the gradient of curve (both RUE and CP) increases and V decreases. RUE: resource use efficiency, CP: cost performance or productivity, and V: vulnerability of (yield $\times$ unit value).

2.4.7 What is “PFAL”?

Definition

Indoor plant production systems can be divided into two types in terms of light source: (1) artificial light only and (2) artificial light and (supplemental) solar light. In this book, the former is further divided into two groups. One is PFALs used mostly for commercial production, consisting of the essential components listed in Table 2.2. The other is the ventilated PFALs and m-PFALs (mini- and micro-PFAL, Chapter 5) used mostly for other than commercial production.

PFALs aim to grow high-value produce (product of the yield and unit value or quality) with maximum RUE and CP, minimum vulnerability of yield and quality of produce, and minimum emission of environmental pollutants. However, PFALs are an emerging and thus technically immature production system, so their commercial application is still very limited.

On the other hand, PFALs have the potential to achieve high RUE, CP, and V and will play an important role in urban areas in the coming decades. This book primarily focuses on PFALs, except for the m-PFAL in Chapter 6 and the rooftop plant production system in Chapter 7.

Scientific benefits of PFALs

Growers can gain the experience of field crop cultivation once or twice a year under changing weather and climate. As for greenhouse cultivation of fruit and vegetables, the experience can be acquired one to four times a year in most cases under a controlled environment, although the cultivation know-how depends on the season and the presence of diseases often caused by pest insects.

In the case of PFAL cultivation of leafy greens or other herbaceous plants, growers can experience seedling production and cultivation of seedlings until harvesting 10–20 times a year under precisely controlled environments. Thus, experience and know-how about PFAL cultivation can be accumulated much faster than for open field and greenhouse cultivation.

During PFAL cultivation, growers can conduct a simple experiment by changing only one factor—for example, the light source, cultivar, or nutrient composition; other factors remain

Table 2.2 Essential components of a PFAL as defined in this book.

No.	Essential component of PFAL
1	Airtight (no. of air exchanges is lower than 0.015 h^{-1})
2	Thermally well-insulated roof and wall (heat transmission coefficient is lower than $0.15 \text{ W/m}^2/\text{C}$)
3	Air shower or hot water shower at the culture and operation rooms
4	Multitiers with lighting system and hydroponic culture beds
5	Air conditioners mainly for cooling (dehumidification at the same time) and air circulation
6	CO_2 enrichment to keep its concentration at around 1000 ppm
7	Floor covered with epoxy resin sheet for keeping it clean
8	Collection and reuse system of water condensed at cooling panel (evaporator) of air conditioners
9	Circulation and sterilization system for nutrient solution supply

Other indoor plant production systems with artificial lighting only are called “o-PFAL (open-PFAL)” or “m-PFAL (mini- or micro-PFAL)” in this book.

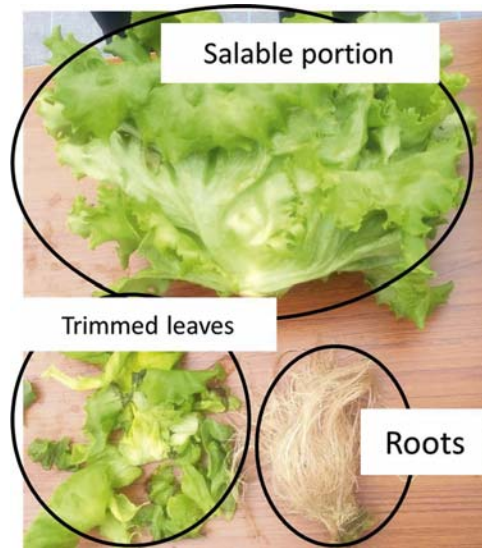
unchanged. This enables the growers to understand the cause—effect relationship easily. Also, the results of PFAL experiments are not affected by the weather, so PFAL experiments are more reproducible than open field and greenhouse experiments. If researchers conduct an experiment using part of a full culture system, there is a high probability that the results can be reproduced in a full-scale culture system. The PFAL manager can also collaborate with researchers at universities or other organizations easily. This is a major benefit of PFALs.

2.4.8 Plants suited and unsuited to PFALs

Plants suited to PFALs for commercial production have the following characteristics: (1) short in height (about 30 cm or less) to be adapted to multitier cultivation racks with a vertical distance between the culture beds of 40–50 cm; (2) fast growing (harvestable 10–30 days after transplanting) at high CO_2 concentration; (3) growing well under low light intensity and at high planting density; (4) high-value product if fresh, clean, tasty, nutritious, and pesticide-free; (5) the product value can be effectively improved by environmental control; (6) about 85% in fresh weight of the plant can be sold as produce (e.g., root weight ratio of leaf lettuce should be lower than 10%–15%) (Fig. 2.16); and (7) any kind of transplant (Chapter 22).

Plants suited to greenhouses using sunlight rather than PFALs for improved quality and yield include: (1) fruit-vegetables such as tomatoes, green peppers, and cucumbers that contain large amounts of functional components; (2) berries such as strawberries and blueberries; (3) high-end flowers such as *Phalaenopsis*, dwarf loquats; (4) mangoes and grapes, etc. for growing in containers with trickle irrigation; and (5) nonwoody or annual medicinal plants such as *Angelica*, medicinal dwarf *Dendrobium*, Asian ginseng, saffron, cannabis, and *Swertia japonica*.

Plants that are not suitable to PFAL production are staple crops used primarily as a source of calories (carbohydrates, protein, and fats) for people and livestock, such as rice, wheat, corn, and potatoes, plants such as sugarcane and rapeseed used primarily as a fuel (energy) source, larger fruit trees, and trees used for timber such as cedar and pine, and others including daikon, burdock, and lotus.

**FIGURE 2.16**

Percentage of fresh weight of salable portion to the total plant weight should be 85% or higher to minimize the electricity consumption per kilogram of the salable portion.

These plants require large areas for growth and have a harvest cycle of several months to 10 or more years, but they have a low ratio of value (price) to mass.

2.5 Growing social needs and interest in PFALs

While PFALs are currently limited primarily to the production of leafy vegetables, they are expected to help alleviate the following social concerns and demands (Kozai, 2013c):

- (1) Concerns over the safety, security, consistency of supply, and price stability of fresh vegetables, particularly the rising demand for purchasing consistency in the catering (restaurants, etc.) and home-meal replacement industries (prepared food and bento retailers) for the elderly and people living alone;
- (2) Demand for highly functional fresh vegetables and medicinal plants arising from concerns about health and improved quality of life;
- (3) Demand for consistent all-year-round production of fresh salad vegetables in cold, hot, and arid regions;
- (4) Demand for greater local self-sufficiency of fresh vegetables to increase employment opportunities for the aged, disabled, and unemployed (PFALs provide a safe and pleasant work environment and enable year-round employment);
- (5) Demand for changes in lifestyle and social population structure in conjunction with convenience stores, supermarkets, restaurants, hospitals, and social welfare facilities, apartment flats, and so forth;

- (6) Demand for new business development in the electrical, information, construction, health care, and food industries;
- (7) Demand for efficient use of vacant land, unused storage spaces, shaded areas, rooftops, and basements in urban areas (Hui, 2011);
- (8) Demand for high-quality transplants for use in horticulture, agriculture, reforestation, landscaping, and desert rehabilitation; and
- (9) Demand for water-saving culture systems in regions with insufficient or saline irrigation water and urban areas [PFALs require only around a 50th of the irrigation water required by greenhouses (Kozai, 2013b)].

Recent technical advances have helped to start the PFAL business, which include improvement of electric energy efficiency, cost performance of lighting, air conditioning, and small information control systems with cloud computing, thermal insulation, electrical energy storage, and generation using natural energy such as solar light, wind, biomass, and geothermal energy (Komiyama, 2014).

Considering the social concerns and demands described here, a social experiment on the introduction of PFALs as part of urban agriculture is underway in accordance with the Smart City Project in Kashiwa-no-ha district, Kashiwa, Chiba, Japan (Fig. 2.17). This city has been built since 2003 to be a sustainable city.

2.6 Criticisms of PFALs and responses to them

2.6.1 Introduction

Community interest in PFALs has grown in recent years as described previously. On the other hand, PFALs have also attracted considerable criticism and concern. We should accept and analyze the criticism earnestly, study the issues from all sides, and search for solutions. When criticisms are based



FIGURE 2.17

Example of an ongoing project on urban agriculture development in Kashiwa, Japan, located 30 min by train from central Tokyo.

on misunderstandings and immature technology, we should clearly explain the true situation based on the facts, and should also improve the technology.

Some typical criticisms of PFALs and urban agriculture (Garnett, 2001; Martin, 2013) are discussed in this section. The numerical data given in the following sections are representative of the PFALs in Japan as of 2014.

2.6.2 Initial cost is too high

In 2014, the initial cost of a PFAL building with all the necessary facilities including 15 tiers with a vertical distance between the tiers of 50 cm was about US\$4000/m² (land area, one US\$ = 120 yen) in Japan. This initial cost is about 15 times that of a greenhouse with heaters, ventilators, thermal screens, and other equipment. The wholesale price of leaf lettuce in 2014 was about US\$0.7–0.8 per head in Japan, so its maximum annual sales/m² is US\$2100–2400 ($= 3000 \times 0.7\text{--}0.8$)/m², compared with the initial cost of US\$4000/m².

On the other hand, annual productivity/m² (land area) of an existing PFAL was about 3000 leaf lettuce heads/m²/year (80–100 g fresh weight per head) compared to that of open fields [32 ($= 16 \times 2$ harvests) heads/m²/year]. This productivity of PFALs is about 100 times that of an open field and about 15 times that of a greenhouse (200 heads/m²/year).

Thus, the initial cost per unit production capacity of a PFAL is more or less the same as that of a greenhouse, although this estimation is rough and varies with many factors. It is difficult to compare the initial cost of a PFAL with that of open fields, which is highly variable. Also, the size and weight of field-grown leaf lettuce heads are often two to three times larger than PFAL-grown ones. On the other hand, the retail prices of field- and PFAL-grown lettuces do not differ significantly in Japan, regardless of the large difference in weight between the two.

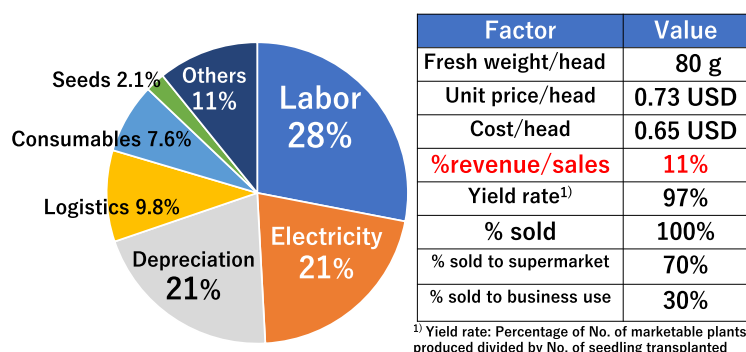
The annual PFAL production capacity given above can be calculated as follows: [20 plants/m² (culture bed area) $\times$ 15 tiers $\times$ 20 harvests/year] $\times$ 0.9 (ratio of salable plants to transplanted plants) $\times$ 0.5 (effective floor ratio of tiers to the total floor area). The other 50% of the floor area is used for the operations room, walkway, seedling production, and equipment. The number of days from transplanting to harvest (80–100 g/aerial part of plant) is 12–15, and from seeding to seedlings ready for transplanting is 20–22.

This annual productivity of PFALs will be improved based on “kaizen” and the PDCA (plan–do–check–action) cycle (Chapter 24) by around 20% within 5–10 years based on improvements in environment control, cultivar suited to PFAL, layout of tiers, and culture methods. The initial cost of PFALs is expected to continue decreasing by a few percent every year in Japan.

2.6.3 Production cost is too high

The component costs for electricity, labor, depreciation, and others of the PFAL using fluorescent (FL) lamps in Japan accounted for, on average, 25%–30%, 25%–30%, 25%–35%, and 20%, respectively. The economic life period for calculating the depreciation differs from country to country. In Japan, it is 15 years for the PFAL building, 10 years for the facilities, and 5 years for the LED lamps.

Fig. 2.18 shows an example of the production cost by components of a-PFAL with LEDs (Ijichi, 2018). Electricity, labor and depreciation are the three major components of the production cost. In another PFAL with FLs located in a local city 500–700 km distant from any large cities, the packing

**FIGURE 2.18**

Percentages of cost components of a PFAL with LEDs producing leaf lettuce in Japan (Ijichi, 2018). Depreciation cost for building and costs for advertising, land etc. are excluded.

and delivery costs account for 12% of the production cost (Ohyama, 2015). If the PFAL is located in or near a large city, the packing and delivery cost would be 6%–8%. Most routine manual operations in PFALs are conducted by part-time workers whose hourly take-home pay is around US\$8–10. In the case of LED-PFAL, electricity cost accounts for less than 20% of the total production cost (Kozai et al., 2016; Kozai, 2018).

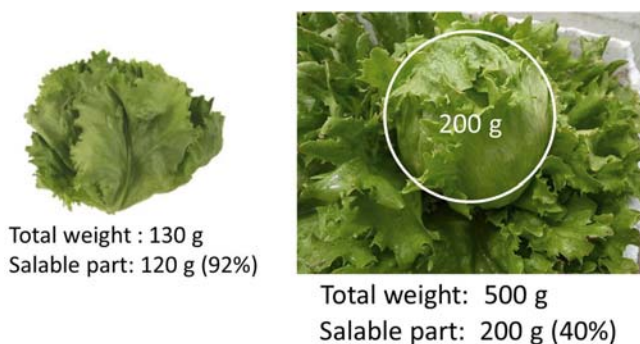
The wholesale price per head was 80–100 yen (US\$0.67–0.83, one US\$ = 120 yen) and the retail price was 150–200 yen (US\$1.25–1.67) in Japan, while it was US\$0.39–0.46 and 0.67–3.5, respectively, in Taiwan (Chapter 3, Section 3.2).

The wholesale prices of leaf lettuce and basil in Japan are, respectively, around US\$8 and \$23/kg. The price of rocket (*Eruca sativa*), watercress, parsley, and low-potassium leaf lettuce (for patients with kidney problems) is around US\$35/kg. The wholesale price is about US\$40/kg for coriander and about US\$70/kg for peppermint and spearmint. Resource and monetary productivities of PFALs in Japan are discussed in detail by Kozai et al. (2019).

It should be noted that, in Japan, the monthly basic charge for electricity is US\$10–12/kW and the consumption charge is US\$0.10–0.12/kWh. Namely, the electricity price in Japan is one of the highest in the world. The costs associated with construction, lighting, and culture tiers are also high in Japan compared with those in many other countries.

In PFAL production cost management, the weight percent of the edible or useable part to the total plant weight is an important index for improving the CP (Fig. 2.16). In PFAL, electric energy is converted to light energy and further converted to chemical energy in plants. Thus, in the case of leafy greens production, electric energy contained in the plant residue (roots and trimmed leaves) needs to be minimized. This is the opposite to the case of field cultivation—in general, the larger the roots, the better the growth and quality (Figs. 2.19 and 2.20).

On the other hand, the roots are indispensable for the intake of water, inorganic fertilizer, and oxygen to support and grow the aerial part. Controlling the root weight to a minimum but not restricting the growth of the aerial part is a key cultivation technique in PFAL production cost management.

**FIGURE 2.19**

Left: Crisp head lettuce plant grown in a PFAL and harvested before head formation at a fresh weight of about 130 g. Ninety-two percent of the total weight is salable. Right: Crisp head lettuce plant grown in the open field and harvested after head formation at a fresh weight of 500 g. Only 40% of the total weight is salable.

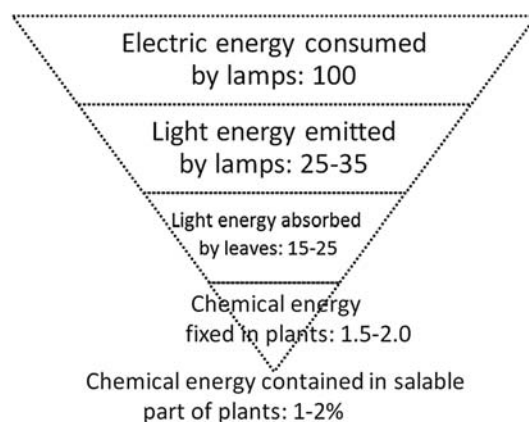
**FIGURE 2.20**

Left: Chinese cabbage grown in a PFAL and harvested before head formation at a total weight of 250 g for a fire-pot meal. Right: Chinese cabbage grown and harvested in the open field after head formation at a total weight of 5 kg.

2.6.4 Electricity cost is too high, whereas solar light is free

Electricity cost accounts for 18%–20% of the total production cost (Fig. 2.18). The electricity consumption of produce per kilogram can be reduced by 20%–30% relatively easily, and by 50%–80% theoretically. Fig. 2.21 shows the energy conversion process in a culture room of an FL-PFAL. The electrical energy fixed in the salable part of plants as chemical energy is 1%–2% at the highest, and less than 1% in most conventional PFALs. The remaining (98%–99%) electric energy is converted into heat energy in the culture room [this is why the heating cost of a thermally well-insulated PFAL even on a very cold winter night (-40°C) is 0].

The electricity cost can be reduced by: (1) using advanced LEDs to improve the conversion factor from electric to light energy; (2) improving the lighting system with well-designed reflectors to

**FIGURE 2.21**

Energy conversion process in current representative PFALs. The value at each step indicates the percentage of the electrical energy consumed. The electrical energy not converted to chemical energy becomes heat energy. [This is why the heating cost of a thermally well-insulated PFAL is 0 even on very cold winter nights (-40°C).].

increase the ratio of light energy emitted by lamps to that absorbed by plant leaves; (3) improving the light quality to enhance the growth and quality of plants; (4) optimally controlling temperature, CO_2 concentration, nutrient solution, humidity, and other factors; and (5) increasing the percentage salable part of plants by improvement of the culture method and selection of cultivars. Once solar light is partially used, all the controllable factors in PFALs become unstable and unpredictable, so this is not a wise choice.

2.6.5 Labor cost is too high

Labor cost accounts for 25%–30% of the total production cost in a PFAL, because most PFALs are small-scale, and most handling operations are conducted manually. It is estimated that a 15-tier PFAL with a floor area of 1 ha needs more than 300 full-time employees, if most handling operations are conducted manually. In this sense, even small-scale PFALs create a significant number of job opportunities and promote local industries. Most manual operations are safe and light work performed under comfortable environmental conditions, and are suited to all persons regardless of age, gender, and whether they are handicapped or not.

On the other hand, in the Netherlands, most handling operations in a greenhouse complex with a floor area of 10 ha or more for production of leafy greens, bedding plants, and transplants are automated, and so need only several employees per ha. Unfortunately, however, those automatic handling systems are too large to be installed in current PFALs.

In recent PFALs with a production capacity of over 10,000 leafy green heads, automation of handling operations is becoming essential to reduce the production cost and to collect and analyze various data automatically. The data include the environment, plant growth, transplanting, harvesting, resource consumption, and the costs, shipping, and sales. PFALs are being automated by using

advanced robotic technologies including remote sensing, image processing, intelligent robot hands, cloud computing, big data analysis, and 3-D modeling.

2.6.6 PFAL-grown vegetables are neither tasty nor nutritious

The taste and nutrition of fresh vegetables are affected by the genetic properties of plants, time courses of physical, chemical, and biological environments encountered by plants, culture systems and methods, and postharvest treatment. It should be theoretically easier to control the taste and nutrition of PFAL-grown vegetables.

In reality, however, the cause—effect relationship between the environment and taste/nutrition in a PFAL for a particular vegetable is still unclear, so PFAL managers do not know exactly how they should control the environment to improve the taste, nutrition, and growth of plants; the environmental control of PFALs is still at the trial and error stage. This is the main reason why the taste and nutrition of PFAL-grown vegetables are sometimes unstable.

On the other hand, an increasing number of researchers at universities and public institutions as well as private companies are accumulating experimental results and know-how on the cause—effect relationships to improve the taste and nutrition of PFAL-grown vegetables and medicinal herbs by environmental control. Once the cause—effect relationships are revealed, PFALs can reproduce the tasty and nutritious vegetables all year round regardless of the weather. In terms of the knowledge and experience of plant production using PFALs, research toward commercialization is still at the initial stage.

One advantage for PFAL researchers is that they can obtain clear cause—effect relationships with less research funds, time, and manpower. It takes time to identify the cause—effect relationships regarding the environment and the taste/nutrition of field-grown vegetables under uncontrollable weather and seasonal changes, even when the cultivar, cultivation system, and postharvest treatment are the same.

The quality and economic value of the vegetables are influenced not only by the taste and nutrition, but also by their safety, which needs to be guaranteed through traceability (Fig. 2.22). The traceability of PFAL-grown vegetables is almost 100% and can mostly be done automatically.

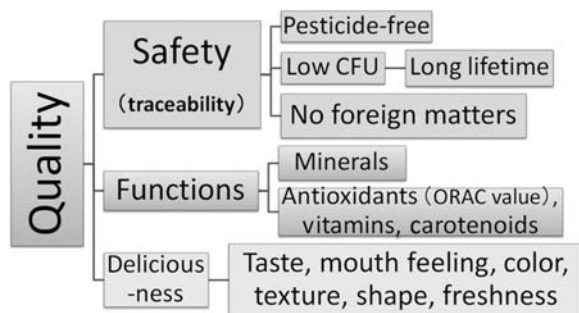


FIGURE 2.22

Factors affecting the quality and economic value of vegetables.

Another issue is that taste and preferences are affected by many factors including social and family cultures, personal history, health conditions, and brand image. Thus, it is natural that many people prefer field-grown vegetables to PFAL-grown vegetables.

2.6.7 Most PFALs are not making a profit

According to a survey in February 2014 by the Ministry of Agriculture, Forestry, and Fisheries of Japan, among 165 PFALs, only 25% made a profit, 50% broke even, and 25% lost money. The survey in 2018 reports that among 215 PFALs, around 50% made a profit. The number of PFALs making a profit has been increasing since 2018 and several large-scale PFALs have been built in 2018 (see Chapter 29).

Visits to the PFALs that were losing money revealed that the PFAL managers did not know that plants need CO₂ for photosynthesis and they were not aware of the necessity of CO₂ enrichment in an airtight PFAL. This lack of knowledge is not surprising because farmers never supply CO₂ gas to their fields and only a limited number of growers supply CO₂ gas in their greenhouses by opening the ventilators. These findings suggest the importance of human resource development and training for PFAL managers to improve their skills.

In order to make a profit, over 90% of PFAL-grown vegetables must be sold at a reasonable price. In reality, however, the production of vegetables is too poor to do so at the PFALs that are losing money. Also, in order to sell all the produce, a “market-in” strategy is more important than a “product-out” strategy. In other words, there is still considerable room for improving the production cost, productivity, and sales strategy.

2.6.8 Land price is too high

The price of land is generally very high in urban areas, while PFALs can be built with little disadvantage in shaded, nonfertile soil and idle land areas. They can be built with little difficulty in empty buildings, office rooms, and industrial factories. PFALs need around 1% and 10% of the land area compared with open fields and greenhouses, respectively, for obtaining the same number of leaf lettuce heads and other leafy greens.

2.6.9 Water consumption for irrigation is too high

As described in detail in Chapter 4, the net water consumption for irrigation in a PFAL is about 2% of that of a greenhouse, because about 95% of the transpired water vapor from plant leaves is condensed as liquid water at the cooling coil panel (evaporator) of the air conditioners, which is collected and returned to the nutrient solution tank after sterilization.

Drained nutrient solution from the culture beds is also returned to the nutrient solution tank after sterilization. Thus, the amount of water to be added to the tank is almost equal to the amount of water kept or held in harvested plants and the amount that escaped outside as water vapor through air gaps. Similarly, the amount of nutrients to be added is almost equal to the amount of nutrients absorbed by harvested plants. Thus, the efficiency of water and nutrient use is over 0.95 and 0.90, respectively, in most cases.

In addition, there is no need to wash the PFAL-grown vegetables before eating, because they are free of pesticides, insects, and foreign substances, so a considerable amount of water can be saved compared with greenhouse- and field-grown vegetables, which must be washed with tap water, electrolyzed water, and/or hypochlorite-added water. Furthermore, since PFAL-grown vegetables are packed in plastic or paper bags immediately after harvest, the loss of vegetables due to water loss and bacteria growth is minimized. Overall, the total water consumption for irrigation and washing of PFAL-grown vegetables can be reduced by 99% compared with that of greenhouse-grown vegetables.

2.6.10 PFALs can only produce leafy greens—minor vegetables—economically

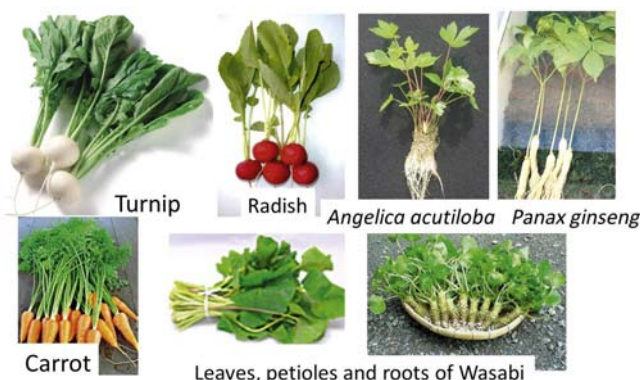
Currently, most PFALs only produce leafy greens including herbs (Fig. 2.23), because they are easy to grow and there is strong demand for PFAL-grown leafy greens. Approximately 150,000 leaf lettuce heads are produced daily in PFALs (18 million heads/year) in Japan as of 2017, which is only 2% of the field-grown leaf lettuce consumption. Commercial production of spinach and other leafy greens in PFALs for fresh salads is currently very limited but will increase significantly within several years. Thus, the total production of leafy greens in PFALs is expected to increase sharply as the cost of production falls.

Small rooted vegetables and medicinal plants have recently started trial production. Examples are turnips, carrots, miniradishes, *Panax ginseng*, and *Angelica acutiloba* (Fig. 2.24). These are all 30 cm in plant height and both the shoots with unfolded leaves and the roots are edible or salable. These plants can be harvested within several weeks after seeding or a few weeks after transplanting. At this growth stage, the shoots are soft and tasty and they make a nice side dish to the main course. These



FIGURE 2.23

Leafy vegetables/herbs commonly produced in PFALs.

**FIGURE 2.24**

Small root vegetables and medicinal plants being produced in modern PFALs. Both shoots with leaves and roots are edible, tasty, and nutritious.

kinds of small roots with shoots cannot be produced in open fields, thus eliminating competition with field-grown vegetables.

Tuberous root vegetables generally grow faster than leafy vegetables under optimal environmental conditions, especially at high CO₂ concentration. This is because the carbohydrates (called “source”) produced in the leaves by photosynthesis can be efficiently moved through sieve tubes in the stem (translocation) into the tuberous roots (called “sink”). Photosynthesis is enhanced as the amount of carbohydrates in the leaves (source tank) tends to be 0 due to the enhanced translocation to the tuberous roots.

If PFAL-grown vegetables are used commercially not only for fresh salads but also as raw materials as shown in Table 2.3, their market size would increase dramatically, creating “a new branch of urban agriculture” or “a new field of food industries.” If the PFAL is well designed and well managed: (1) the

Table 2.3 Range of uses of PFAL-grown plants in the coming decades.

No.	Expected uses
1	Fresh salads and cut (sliced) vegetables
2	Frozen vegetables and dried vegetables
3	Paste, sauce, soft drink, drink additives, jam, and juice
4	Pickles, salted vegetables, and kimchi (Korean pickles)
5	Vegetables for fire-pot meal, fried and soup vegetable dish
6	Cosmetics, dyes, aromatics, and spices
7	Medicinal plants for herbal medicine and supplements
8	Functional foods and pharmaceuticals (e.g., vaccine)
9	Transplants of all kinds, mother plants for propagation
10	Strawberry, blueberry, raspberry, and blackberry

production cost per kilogram can be reduced by 30%; (2) the economic value per kilogram can be increased by 15%; and (3) the initial cost can be easily reduced by 30% by 2023 (Kozai, 2018).

If we could achieve these targets, PFALs could be used at any local and/or rural area to grow high-value crops for processed food materials. The harvested plants would be dried (after boiling), powdered in some cases, and stored there for 1–6 months. Then, they would be taken to a food factory for further processing. In this way, PFALs could be used in any area far from urban areas, where people living in cold, hot, or dry areas could work inside the PFAL under comfortable conditions.

2.7 Toward a sustainable PFAL

2.7.1 Requirements for a sustainable PFAL

PFALs must be improved to build a sustainable plant production system. A systematic and scientific methodology to realize sustainable PFALs is proposed in this book, although the methodology requires continuous revision and refinement. For PFALs to be sustainable, they must satisfy the following requirements:

- (1) They should make simultaneous and parallel contributions to solving global food, environment, resource, and social issues;
- (2) The entire plant supply chain from production to consumption should be resource saving and have low CO₂ emissions. In particular, PFALs should dramatically cut the use of water and petrochemicals by greatly reducing the direct use of oil-based products and completely eliminating the use of pesticides and fossil fuels for heating, even on very cold winter nights;
- (3) They should contribute to protecting the environment by minimizing the release of environmental pollutants;
- (4) They should maximize the use efficiency of resource investment (ratio of utility value or rate of conversion of resources to products to the amount of resources committed) and maximize the efficiency of using natural energy;
- (5) They should increase the stability of the production system in the face of abnormal weather patterns and the presence of contaminants, and deliver planned high quality and high yield all year round;
- (6) The systems should be safe and pleasant for the operators and local residents, and contribute to creating an industry in which environmental health and welfare can coexist;
- (7) They should expand employment opportunities and give meaning to life for a broad range of people, including the aged and disabled;
- (8) The system as a whole, including its operators, should evolve appropriately with changes in the natural environment and the diverse social environment; and
- (9) They should facilitate international technology transfer through the development of standardized systems.

The scientific and engineering aspects of PFALs are described in Chapter 4.

2.7.2 Factors affecting the sustainability of PFALs

Positive aspects affecting the environmental, resource, social, and economic sustainability of PFALs as well as issues to be solved to improve the sustainability of PFALs are summarized in the following sections.

Positive aspects affecting environmental, resource, social, and economic sustainability

- A. Environmental and resource sustainability**
 - (a) Reductions in: (1) water for irrigation; (2) water for washing products; (3) pesticide application; (4) fertilizer leaching to drains; (5) unusable and/or unsalable parts of plants; and (6) distance for food transportation.
 - (b) Promotion of recycling use of: (1) drained water and nutrient solution.
 - (c) Improvements in: (1) resource use efficiency (RUE).
- B. Social sustainability**
 - Increase in local employment.
- C. Economic sustainability**
 - (a) Increases in: (1) yield and quality of products and their decreased vulnerability; (2) local fresh food production and sales; (3) local food security and safety; (4) fresh leafy greens edible without washing; and (5) longer shelf life.
 - (b) Reductions in: (1) land area per yield (more amenity space for exercise and recreation) (Fig. 2.25); (2) loss of produce; and (3) working hours for plant production per yield.

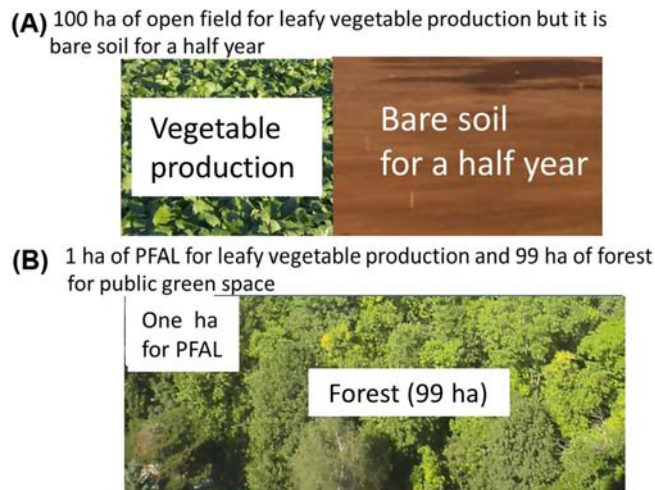


FIGURE 2.25

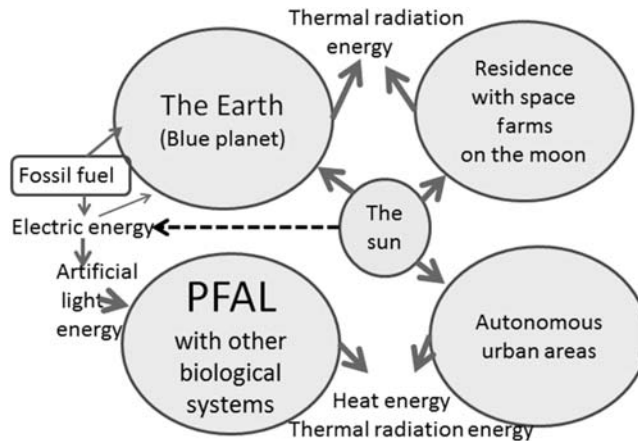
Productivity of leafy greens using a PFAL is over 100 times that of open fields which is more sustainable with respect to the environment, resources, society, and economy: A or B?

Factors to be solved to improve sustainability

- (a) Reductions in: (1) electricity consumption for production and product cooling and (2) materials and energy consumption for building construction.
- (b) Increases in: (1) recycling use of organic waste including plant residue for composting, biofuels, CO₂ for promoting plant photosynthesis and other purposes; (2) biodiversity around PFALs in urban areas; (3) amenity space around PFALs for exercise and recreation; and (4) aesthetic value.
- (c) Promotion of: (1) active community participation; (2) social inclusion: providing fresh food to the poor; (3) education; and (4) software development for design and production management.

2.7.3 Similarities between the Earth, space farms, autonomous cities, and PFALs

In the design and operation of the PFAL with other biological systems toward a sustainable system, the Earth and a virtual residence with space farms on the moon are good natural and artificial models, respectively (Fig. 2.26). Both are closed systems with respect to materials, while they are open systems with respect to radiation energy—receiving solar (short-wave) radiation and emitting thermal (long-wave) radiation. All of the systems require plant production systems with high yield and quality in a limited space using minimum resources with minimum emission of environmental pollutants. Controlling the balance of materials and energy flows within the system and between the system and its environment is essential to create a sustainable system. There is an urgent need to minimize the consumption of fossil fuels without reducing the yield and quality of crops both in soil and in PFALs by using natural energy more efficiently.

**FIGURE 2.26**

The Earth and virtual residence with space farms on the moon are both closed systems with respect to materials and are open systems with respect to radiation, receiving solar radiation and emitting thermal radiation. They are models of PFALs with other biological systems and autonomous (local production for local consumption) urban areas. All the systems require plant production systems with high yield and quality in a limited space using minimum resources and emitting minimum environmental pollutants to be sustainable. There is an urgent need to minimize the consumption of fossil fuels without reducing the yield and quality of crops both in soil and in PFALs by using natural energy more efficiently.

2.8 Conclusion

This chapter discussed the reasons behind the increasing importance of fresh food production in urban areas, and presented examples of how efficient production could be achieved. First, resource inflow and waste outflow in urban areas were shown. Then, it was pointed out that a large portion of urban waste can be used as an essential resource for growing plants in urban ecosystems, thus significantly reducing resource inflow and waste outflow. The criticisms that urban agriculture is not economically viable and that PFALs make heavy use of electricity, have high production costs, and are not financially viable were also addressed. It was shown that PFALs can produce value-added plants at high yield with minimum resource consumption and environmental pollution, and can contribute to partially solving several important issues occurring in urban areas by producing fresh foods using PFALs in combination with other biological systems.

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PFAL business and R&D in Asia and North America: status and perspectives

3.1 Introduction

This chapter briefly describes the history, status, and perspectives of plant factories with artificial lighting (PFAL) in Japan, Taiwan, China, Thailand, and North America, including research, development, and business. The governmental subsidy for PFAL research and development (R&D) and business in Japan is introduced. Taiwanese companies have started to export and build turn-key PFALs abroad. PFALs have been developing rapidly in China since 2010. The Chinese Academy of Agricultural Sciences (CAAS) started a national project on intelligent plant factory production technology in 2013 supported by the Ministry of Science and Technology. The Institute of Urban Agriculture was built in 2018 at Chengdu City, Sichuan Province, supported by CAAS. In Korea, the Ministry of Knowledge Economy (MKE) started a research project named “Development of major components for IT-LED-based plant factories” in 2009. The annual domestic market of the PFAL business in Korea was worth nearly US\$600 million in 2014. In the USA, several large-scale commercial facilities were recently built to produce leafy greens, herbs, and microgreens. More recently, large commercial PFAL facilities were built close to large cities such as Newark in New Jersey. The perspectives of the PFAL business and R&D in Asia and North America are discussed.

3.2 Japan

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The history and status of the PFAL business as well as R&D in Japan are briefly described. Then, the governmental subsidy for PFAL R&D and business, which was introduced in 2009, is explained. Finally, recent public service activities for PFAL are outlined.

3.2.1 Brief history and current status of the PFAL business

In Japan, the first commercial PFAL, Miura Nouen in Shizuoka Prefecture, was established in 1983. This was followed in 1985 by a PFAL at a vegetable sales area in a shopping center in Chiba Prefecture. By the mid-1990s, high pressure sodium lamps were being used as light sources. Since the

surface temperature of the lamps is over 100°C, the lamps must be located beyond 1 m from the plant community.

In the late 1990s, fluorescent lamps became preferred mainly due to their higher PAR (photosynthetically active radiation; wavelength, 400–700 nm) output per watt. Then, PFALs consisting of multitiers (4–15 racks) with a vertical separation of about 40 cm between tiers became available. PFALs using LEDs as their light sources began to be commercialized in 2005 in Japan but were not very popular until 2015.

The number of PFALs in Japan for commercial production was 34 in 2009, 64 in 2011, 106 in 2012, 125 in 2013, 165 in 2014, and 186 in 2017. Until 2015, most PFALs were installed with fluorescent lamps. Since 2015 the number of PFALs with LEDs has increased, while the number of PFALs with fluorescent tubes has decreased. The total number of PFALs remained almost unchanged during 2015 and 2017.

In addition, closed plant production systems with artificial lighting (CPPS) units with a floor area of 16.2 m² for transplant (seedlings and plantlets from cuttings) production were commercialized in 2004 and were in commercial use in 2014 at around 300 locations throughout Japan, and with some also in Australia (see Chapter 21).

At the end of 2018, the largest PFAL with LEDs, Techno FarmTM, was built in Kyoto with a production capacity of 30,000 leaf lettuce heads (120 g per head) daily by Spread Co., Ltd (see Chapter 28). A PFAL with all LEDs producing 10,000 leaf lettuce heads daily was built by Mirai Co., Ltd. in Tagajoh, Miyagi Prefecture, in March 2014 (see Chapter 28). Fig. 3.1 shows the PFAL built in June 2011 at Kashiwa-no-ha Campus, Chiba University, operated by Mirai Co., Ltd. On the same campus, another PFAL was built in September 2014 by Japan Dome House Co., Ltd (see Chapter 28). In the campus of Osaka Prefecture University, a PFAL with all LEDs was built in September 2014, which can produce 5000 leafy greens daily (see Chapter 25).

The size of the PFAL business market is still very limited, and was probably worth about 12 billion yen (1 US\$ = 120 yen) in 2014, and 25 billion yen in 2017. It is expected to be worth 50–60 billion yen by 2021. According to a survey by the Ministry of Agriculture, Forestry and Fisheries (MAFF) published in March 2014, (1) 75% of PFALs are operated by private companies (the rest are operated mostly by incorporated agricultural organizations); (2) 55% of PFALs have a floor area of less than 1000 m² including the operation room and office; (3) 75% of PFALs have annual sales of less than 50 million yen; (4) 75% of PFALs use fluorescent lamps as the light source; and (5) 35% of PFALs received both a subsidy and loan, 30% received neither subsidy nor loan, 20% received a loan, and 15% did not answer. The initial and operation costs are given in Chapter 2. The negative situation

FIGURE 3.1

PFAL at Chiba University built in 2011, operated by Mirai, Co., Ltd. Total floor area: 406 m²; floor area of culture room: 338 m², 10 tiers, nine rows. Mainly leaf lettuce and romaine lettuce; 3000 heads per day (1 million heads/year or 2800 heads/m²/year).



**FIGURE 3.2**

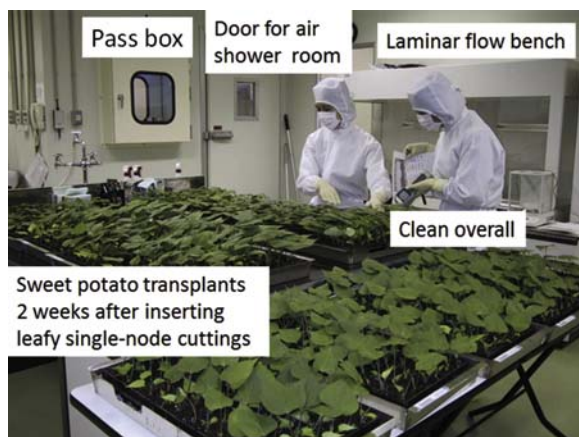
The closed plant production system (CPPS) with seven tiers for disease/pest insect-free transplant production, built in 2000 at the Matsudo Campus of Chiba University. An automatic tray-handling/transportation system, automatic precision irrigation system, and distributed intelligent control system were installed.

described above has been changing since 2017, and the number and percentage of PFALs making a profit have been increasing significantly.

3.2.2 Research and development

Research in Japan on plant production under artificial light aiming at commercialization was begun in the mid-1970s by Takakura et al. (1974) and Takatsuji (1979). The Japanese Society of High Technology in Agriculture, which was established in 1989 focusing on plant factory research, was merged in 2005 with the Japanese Society of Agricultural, Biological and Environmental Engineers and Scientists. This academic society has been organizing one-day symposiums (the “SHITA Symposium”) on plant factories in January every year since 1990. Takatsuji was a group leader of PFAL R&D at the Numazu Campus of Tokai University from 1991 to 2007.

In 2000, a CPPS was built for R&D at Matsudo Campus, Chiba University (Kubota and Chun, 2000; Chun and Kozai, 2001) (Figs. 3.2 and 3.3). This PFAL was designed and operated based on the concept of the CPPS (Kozai and Chun, 2002; Kozai et al., 2006). In this PFAL, handling of culture plug

**FIGURE 3.3**

Operation room next to the culture room. Disease-free, pest insect-free, and pesticide-free sweet potato transplants were propagated. The substrate was autoclaved before use.

FIGURE 3.4

Production of medicinal plants in the CPPS. Left: St. John's wort (*Hypericum perforatum* L.) (Zobayed et al., 2006, 2007). Right: *Glycyrrhiza uralensis* (Afreen et al., 2005, 2006).



trays and operation of the precision irrigation system were automated (Ohshima et al., 2005). Using the PFAL, the production of disease-free sweet potato transplants, tomato seedlings, and medicinal plants were studied (Afreen et al., 2005, 2006; Zobayed et al., 2006, 2007) (Fig. 3.4).

Base on the concept described above, CPPS units with fluorescent lamps for transplant (seedling) production commercialized in 2004 were developed (Kozai, 2007). The same concept was used to develop the sugar-free medium (photoautotrophic) micropropagation system (Kozai et al., 2005).

In 2009, the Ministry of Agriculture, Forestry and Fisheries (MAFF) and Ministry of Economy, Trade and Industry (MITI) started the national project “Plant factory with artificial light and/or solar light” with a total budget for 5 years of 15 billion yen (1 US\$ = 120 yen). The former provided subsidies for demonstration, training, extension, and publicity, and the latter provided subsidies for basic research. Private-sector companies could apply for a 50% subsidy from the above budget to build PFALs for commercial use. This national project was terminated in 2014.

Osaka Prefecture University and Chiba University received budgets for PFALs from both MAFF and MITI. Meiji University, Shinshu University, and Shimane University received budgets for PFALs from MITI. The National Agriculture and Food Research Organization (NARO) received a budget for PFALs from MAFF, which covered the construction of the PFAL building and basic infrastructure, while expenses for facilities inside the building were covered by the consortium members (private sector) of each project site.

Apart from these projects, Tamagawa University, Yamaguchi University, and Kyoto University and several other universities have been conducting R&D on PFALs since 2010. Also, many private companies started investigating the PFAL business using their own budgets.

In March 2011, the Great East Japan Earthquake struck the northeastern coast of the main island of Japan, and the ensuing tsunami hit the Pacific coast of Fukushima, Miyagi, and Iwate prefectures (destroying three nuclear power plant units in Fukushima). Since agriculture and horticulture are important industries in those areas, the Japanese government provided subsidies to build new greenhouses and PFALs in 2012 and 2013. In November 2014, the International Plant Factory Conference was held in Kyoto and Osaka attracting 160 participants including 60 overseas participants (<http://www.shita.jp/ICPF2014/>).

3.2.3 Public service

In June 2010, the Japan Plant Factory Association (JPFA), a nonprofit organization, was established in the Kashiwa-no-ha Campus of Chiba University. The number of JPFA corporate members was 60 in

2010, 98 in 2014, and 145 in 2017. JPFA has two roles: one is collaboration with Chiba University and the other is collaboration with national and international organizations, offering monthly half-day seminars, monthly 22- or 3-day training courses, consulting services, guided tours for visitors to the campus, and collaborative R&D with the corporate member companies (see Chapter 27). PFAL organized a 5-day training course on PFAL in English in October 2018. In 2012, an association for PFAL managers was established, and was renamed and reorganized in 2016 as the Japan Plant Factory Industry Association (JPFIA) with 12 corporate members.

There are several exhibitions with conferences related to the PFAL business, including: (1) Agro-innovation held at Tokyo Big Sight every year (<http://www.jma.or.jp/ai/en/>) organized by the Japan Management Organization, (2) Greenhouse Horticulture & Plant Factory Exhibition held at Tokyo Big Sight every 2 years (<http://www.gpec.jp/english/>) organized by the Japan Greenhouse Horticulture Association, and (3) AgriWorld at Makuhari Messe (<http://www.agritechjapan.jp/en/tokyo/>) by Reed Exhibitions Japan Ltd.

3.3 Taiwan

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The global trend of population expansion is clear: it is estimated that the world population will increase from 7 to 9.6 billion in less than 40 years. It is also estimated that 70% of the population will be living in urban areas compared with the current 50% (Kozai, 2014). There is no doubt that urban agriculture will expand, and PFALs (plant factories with artificial lighting) can play an important role in feeding this growing population. As pointed out by Glaeser (2011), the development of urban areas should be vertical instead of horizontal to conserve land and resources. The same is true for the development of urban agriculture and thus the use of PFALs (or vertical farming) is essential. Since 2010, the PFAL industry has been booming worldwide. It is currently in the third wave in Japan and the first wave in Taiwan. Thanks to advances in technology, the development of LEDs has made PFALs not only technologically feasible but also economically attractive. Numerous businesses have tried out this new technology using a variety of business models. The invaluable experience accumulated throughout almost a decade allows us to answer challenging questions, such as “What caused the company to fail?,” “What caused the production to fail?,” and “What are the risks?” This section briefly discusses the status of PFALs and the PFAL-related Expo held in Taiwan. More attention is given to PFALs related to research and the business models used in the PFAL industry in Taiwan.

3.3.1 Status of PFALs in Taiwan

From 2013 to June 2018, the number of organizations engaged in PFAL production of leafy greens in Taiwan increased from 61 to 134. Among these organizations, PFAL-related experimental stations/labs/centers established in universities and research institutes increased from 12 to 17. Tracing back to 1993, only one university was involved in PFAL research and not a single commercial PFAL company existed.

PFALs built by universities and research institutes are financially supported by internal funds and the government; however, private companies do not receive financial support from the government. Among those PFALs, 62%, 17%, and 21% are located in northern, central, and southern Taiwan,

respectively. PFALs are categorized into three sizes based on the daily harvest, ranging from the smallest (<300 plants/day) to the largest (>10,000), assuming a cropping density of 25 plants per square meter of the culture bed. Half of those PFALs are small with daily production of less than 300 plants and only one PFAL has a daily production of more than 10,000 plants. The largest PFAL has a daily harvest of 2.5 tons of leafy greens. Over 90% of the PFALs are small enough to occupy a single room or basement in a large office building or industrial factory. The only PFAL in the agricultural zone in Taiwan was built inside a greenhouse.

Successful PFALs have been renovated from discarded assets, which can revitalize the local economy by providing job opportunities and producing local, fresh food. This can also lead to reduced transportation costs and a smaller carbon footprint.

Some companies started exporting and building turnkey PFALs abroad, mainly in China and southeast Asia. So far, a total of 15 projects have been initiated and several have been completed. Among the 15 PFALs, 4 were built in the companies' own branches located in China. The largest was built by Foxconn and is located in Shenzhen, China. A Taiwanese company is behind this construction, and these are the first PFALs to use organic liquid fertilizer in Taiwan. The floor area of Foxconn's PFAL is 5000 m² and the daily production is 2.5 tons of vegetables. More information on these two companies can be found in Chapter 31.

3.3.2 PFAL expo in Taiwan

To further promote the use of PFALs, related technical books were translated (Kozai, 2009, 2012; Takatsuji, 2007; Fang, 2011a, 2011c, 2012). In addition, booklets and books (Fang, 2011b; Fang and Chen, 2014) for the general public were published. Exhibitions and conferences were organized by the Photonics Industry & Technology Development Association (PIDA) of Taiwan, which has also held the Photonics Festival in Taipei, Taiwan, for 27 consecutive years. PIDA is an NPO established by the Taiwan government to assist the optoelectronic industry in Taiwan. Apart from organizing exhibitions, the PIDA also provides services such as industry research, consultation, promotion, and communication to the industry and market. PFALs have been included in the festival since 2012. Another two NPOs, the Taiwan Plant Factory Industrial Development Association (TPFIDA, founded in 2011) and the Chung-Hwa Plant Factory Association (CPFA, founded in 2012), were major co-organizers. The number of booths related to PFALs increased from 36 in 2012 to 108 in 2014. Starting in 2015, the two organizations held separate exhibitions and the number of booths shrank. Apparently, some of the larger and more established companies considered themselves well-known in Taiwan and no longer participated in the expos.

Among the PFAL booths throughout the years, most companies demonstrated the hardware used in PFALs. Several of them showed the various spectra and controls of LED tubes and panels. Some showed locally developed or imported nutrient control systems. Several booths from Japan showcased the PFAL turnkey capability and automatic fertigation equipment. Some booths from the Republic of Korea showed wireless LED light sources and LED chips. Also, several local companies conveyed their capability in setting up PFALs abroad. More than seven companies demonstrated a home appliance style plant growth desktop device and three showed plant growth benches to be used in shops/restaurants/supermarkets with or without environment control capability. The 2014 Expo included an LED illuminated green wall with air-cleaning capability. The company works together with construction companies to have the system embedded into buildings. They have successfully

exported the green wall and plant growth desktop device to Macao and Handan cities in Hebei Province in China. One company showed an aquaponics system and another company showed a variety of processed food products with PFAL-grown vegetable ingredients. They participated in the Expo every year up to 2015 and have become very successful. They opened a branch in Xiamen (China) in 2016 for marketing their food products and are planning to set up a production PFAL, a research center, and a marketing office in Singapore in 2018.

3.3.3 PFAL research

Cost comparison of PFALs

Crops grown in PFALs can be separated into four types: RTC (ready to cook), RTE (ready to eat), CAW (cook after washing), and EAW (eat after washing). The retail price of RTE lettuce and CAW pak choi varies from NT\$500 to NT\$2000 and from NT\$200 to NT\$300 per kg, respectively. Table 3.1 shows the average retail price and cost of lettuce produced from similar PFALs in Japan and Taiwan. There are some fundamental reasons for the dramatic difference in production costs. Mainly, the high cost of construction and equipment, especially for LEDs, leads to high depreciation and labor costs. The cost of electricity also adds to high operating costs.

Spectra of LEDs used in PFAL

Fig. 3.5 shows the spectra of artificial light used in PFALs in Taiwan. Assuming culture beds of the same size (1.8×1.2 m), the light use efficiency under various lighting conditions after installation and before growing any plants is compared in Table 3.2. The row with a shaded background shows that the LED panels are generally less efficient compared with LED tubes with reflective film between the tubes. Also, the longer the tube, the higher the overall efficiency in terms of quantitative measures using micromoles per joule as the unit. This value is defined as the quantum energy (QE) ratio. By definition, the QE ratio is not the same as the light efficiency (PPF/W) provided by the manufacturers, although both are in the same units (micromoles per joule). At present, the PPF/W is less than 2.5, but the QE ratio can be as high as 4.2 with the use of reflectors and white grow panels.

WSN in PFAL

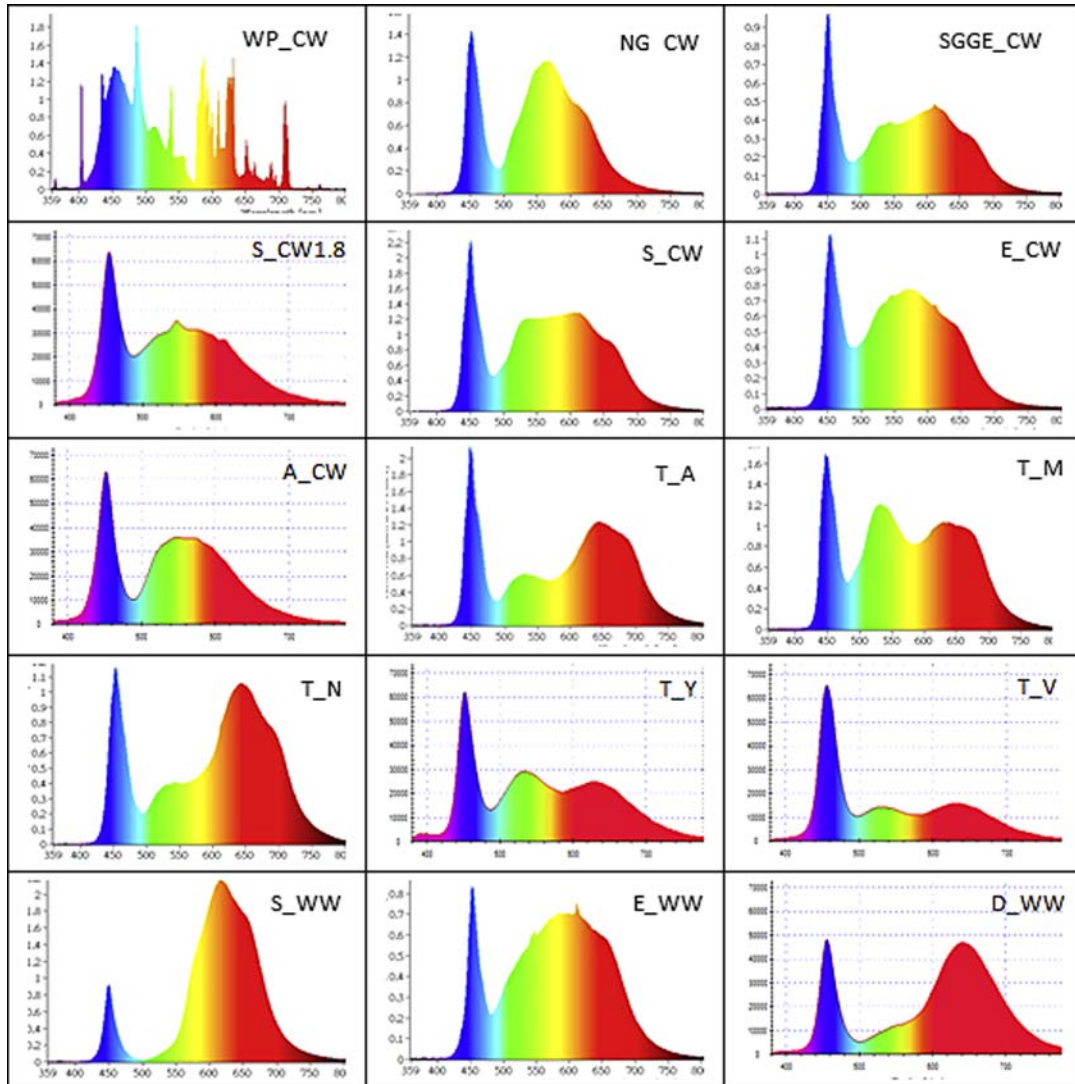
A wireless sensor network (WSN) is used to evaluate the uniformity of air temperature, humidity, and light intensity horizontally in each layer and vertically within the layers of a PFAL (Cheng et al., 2011;

Table 3.1 Comparison of retail price and cost of lettuce produced in PFALs in Japan and Taiwan.

Lettuce	Japan	Taiwan
Retail price ^a	¥150–200	¥81–420 ^b
Cost ^a	¥80–100	¥47–56 ^b

^aIn Japanese yen per 70 g fresh mass produced.

^bExchange rate: 1 NT\$ to 3 Japanese yen.

**FIGURE 3.5**

Spectra of various artificial lights used in PFAL (Fang, 2014).

Juo et al., 2012). Each wireless sensor module is equipped with temperature, relative humidity, and light sensors hanging above the crops in each layer of the culture benches to verify the uniformity of light and air distribution. As shown in Fig. 3.6, the temperature distribution is clearly related to the distribution of the fresh weight harvested. This means that the increase in uniformity of the temperatures helps to reduce the variation in final fresh weight. A smart fan system enables this capability (Lee et al., 2013).

Table 3.2 Comparison of “quantum energy ratio” of various light sources used in PFAL (Fang, 2014).

Light source ^a	Reflectors on top	Number of tubes or panels	PPFD ^b ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	PPFD $\times$ area ^c ($\mu\text{mol s}^{-1}$)	Power consumption (W)	QE ratio ($\mu\text{mol J}^{-1}$)
S_CW1.8	Y	6 tubes	334.9 $\pm$ 86.6	723.4	172.97	4.2
T_V	Y	9 tubes	281.6 $\pm$ 59.4	608.4	195	3.1
H_CW	Y	9 tubes	273.9 $\pm$ 79.8	73.9	212	3.1
T_A	Y	9 tubes	225.8 $\pm$ 49.1	487.8	189	2.6
E_CW	Y	9 tubes	263.8 $\pm$ 64.2	569.8	228	2.5
T_A	No need	12 panels	411.5 $\pm$ 103.2	888.9	432	2.1
T_N	Y	9 tubes	186.7 $\pm$ 39.3	403.2	196	2.1
E_WW	Y	9 tubes	210.8 $\pm$ 51.0	455.3	229	2.0
T_N	No need	12 panels	378.4 $\pm$ 95.4	809.6	428	1.9
T_M	Y	9 tubes	168.0 $\pm$ 39.1	326.9	193	1.9
T_M	No need	12 panels	387.3 $\pm$ 99.4	836.5	442	1.9
T_Y	Y	9 tubes	168.3 $\pm$ 34.7	363.5	188	1.9
S_R	No need	12 panels	291.0 $\pm$ 71.3	628.6	334	1.9
T5FL_CW	Y	9 tubes	250.0 $\pm$ 57.5	540	283	1.9

CW 1.8, Cool White LED tubes with 1.8 m in length; V, A, N, M, Y and R, codes for LED tubes or panels of company T; WW, Warm White LED tubes; R, code for LED tubes or panels of company S, FL, Fluorescent lamps.

^aCharacter(s) before underline, ‘_’, indicates company name; character(s) after underline indicate type of light source.

^bMeasured at 10 cm distance under light except the T5FL treatment (at 20 cm distance).

^cArea of culture bed on bench layer = 1.8 $\times$ 1.2 m = 2.16 m².

Ion-selective sensors for nutrient detection

Traditional ion-selective sensors are quite expensive and have a short useable lifespan. However, newer ion-selective sensors have been developed for the detection of macroelements in nutrient solution. Fig. 3.7 shows the sensing responses of screen-printed ion-selective electrodes (ISEs) for Ca²⁺, K⁺, Mg²⁺, NH⁴⁺, and NO³⁻.

Nondestructive plant growth measurement system

A measurement system using cameras attached to a sliding rail on each layer of a culture bench together with weighing devices for each plant was developed for continuous and automatic plant growth measurement. The system can take images at a preset time interval and then stitches together all the images across the culture bed to form a panoramic view of the culture bed using a computer with image processing capabilities. In the recording process, the cameras move across the entire culture bed to acquire images. Temperature and humidity sensors are also integrated with the imaging system to acquire spatial-temporal environmental information during the plant growth period. Image processing algorithms that calculate geometric features such as the projected leaf area, plant height, volume, and diameters were developed and incorporated into the automated measurement system (Yeh et al., 2014). The accompanying automatic weighing system using load cells was also developed to record the fresh

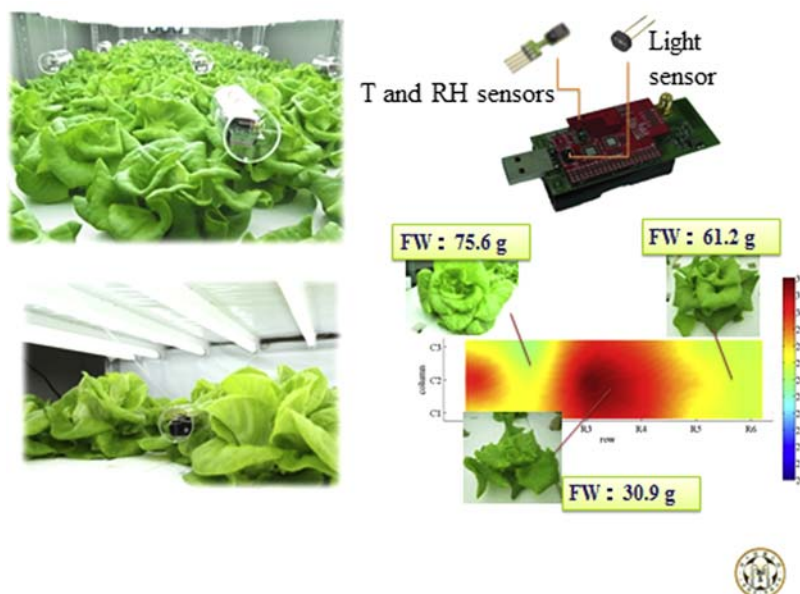


FIGURE 3.6

Wireless sensing nodes in PFAL.

weight of individual plants throughout the entire growth period. The weighing system can also be applied to measure plant growth as an independent system. Fig. 3.8 shows a schematic diagram of the plant growth measurement system. For the weighing system, the load cell signals are calibrated, acquired, and displayed in real time. The data are analyzed in correspondence with the plant geometric features obtained from the imaging system, allowing the derivation of plant growth models under various controlled environmental conditions. This plant growth measurement system provides a nondestructive and real-time processing approach over the traditional measuring methods. Furthermore, the automation feature of the system makes it possible to easily gather a large number of plant measurements. Hence, the system is an efficient and practical tool for optimizing the growing environment parameters in a plant factory system.

LED tubes with adjustable spectrum and intensity

It is well known that for seedling production, vegetables prefer more blue light than red light. But for vegetative growth after transplanting, vegetables prefer more red than blue. It is easy to mistakenly think that green leaves reflect green light, and thus do not need green light. Based on recent research, it is recommended that a wide light spectrum is better than a narrow spectrum with just R (600–700 nm) and B (400–500 nm). However, the fact that plants do not need too much green light is also well known. For regular indoor illumination, the cool white, warm white, and daylight LED tubes provide too much (more than 45% of PAR) green light (500–600 nm). These light sources may be the cheapest, but they are not the best ones for plants.

For our research, we developed four types of LED lamps: R/B, R/W, R/W/B, and R/FR. The spectrum and intensity of light can be adjusted without having to replace the lamps or change the

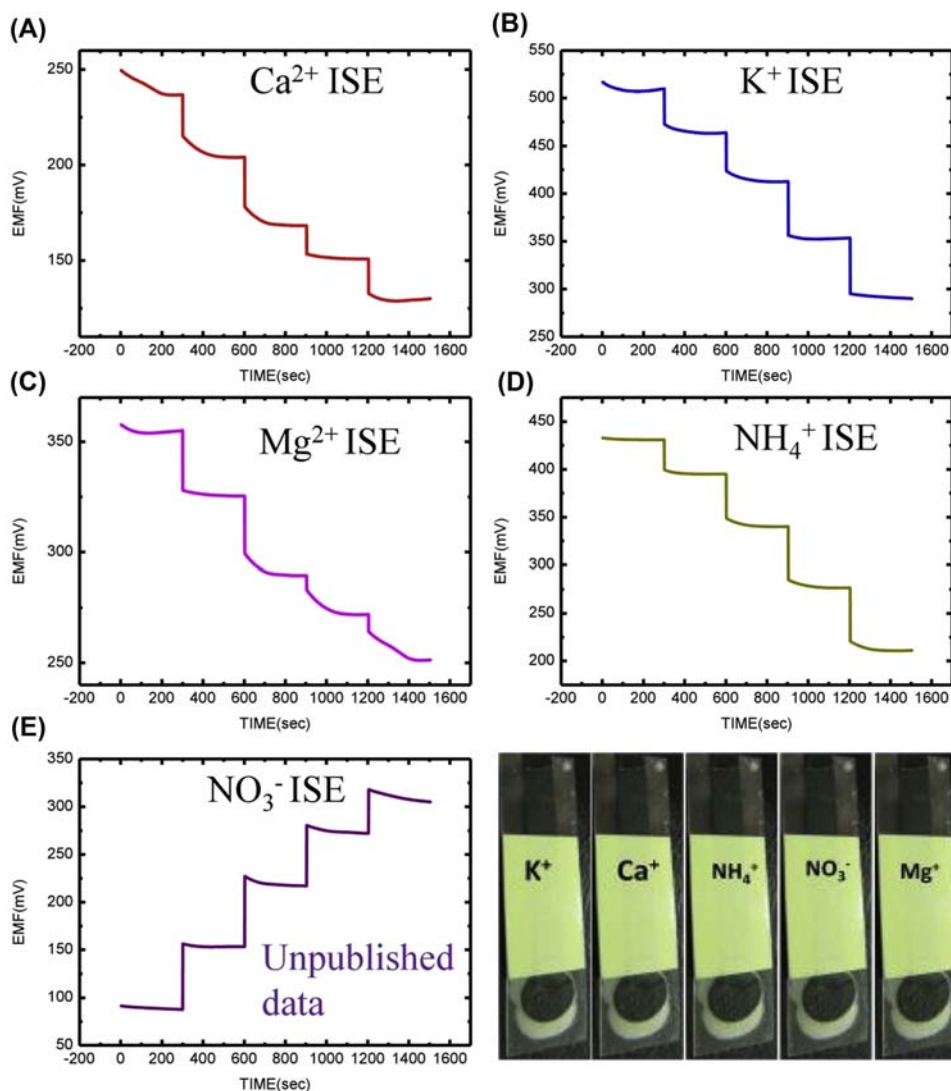
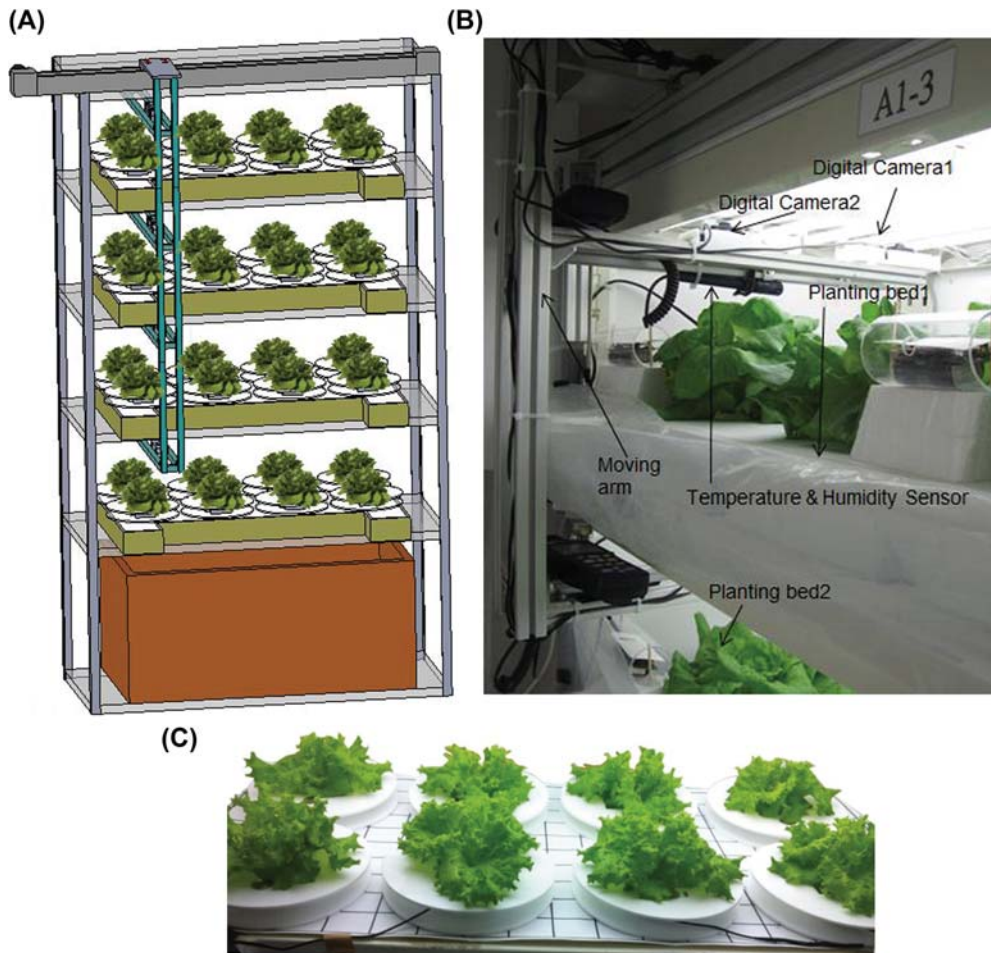


FIGURE 3.7

Sensing responses of screen-printed ion-selective electrodes (ISEs) for Ca^{2+} , K^+ , Mg^{2+} , NH_4^+ , and NO_3^- .

distance from the lamps to the plants. Fig. 3.9A and B show the spectra of R/B and R/W/B LED tubes at various R/B ratios, respectively. For R/B adjustment, there are 21 spectra that can be chosen by selecting the desired R/B value in the wired controller or with the wireless module using a smart phone. For R/W/B adjustment, there are 19 spectra available.

**FIGURE 3.8**

Nondestructive plant growth measurement system. (A) Schematic diagram of the system, (B) imaging system integrated with temperature and humidity sensors, (C) plant weight measurement devices.

Fig. 3.10 shows the spectra comparisons of R/W/B (three spectra at the upper portion) and R/W (three spectra at the lower portion) LED lamps at R/B ratios of 1, 4, and 7 (from left to right). Included in the background of the spectra is the McCree curve showing the photosynthesis response of green leaves. As shown in the lower portion, for R/W adjustment, there are always more green photons than blue photons. This might not be favorable to plants; thus, R/W/B tubes were developed. As shown in the upper portion, for R/W/B adjustment, there are always fewer green photons than blue photons. The energy to produce green light is now shifted to generate red and blue light.



FIGURE 3.9

(A) Spectra of “R/B adjustable” LED tubes at various R/B ratios., (B) Spectra of “R/W/B adjustable” LED tubes at various R/B ratios.

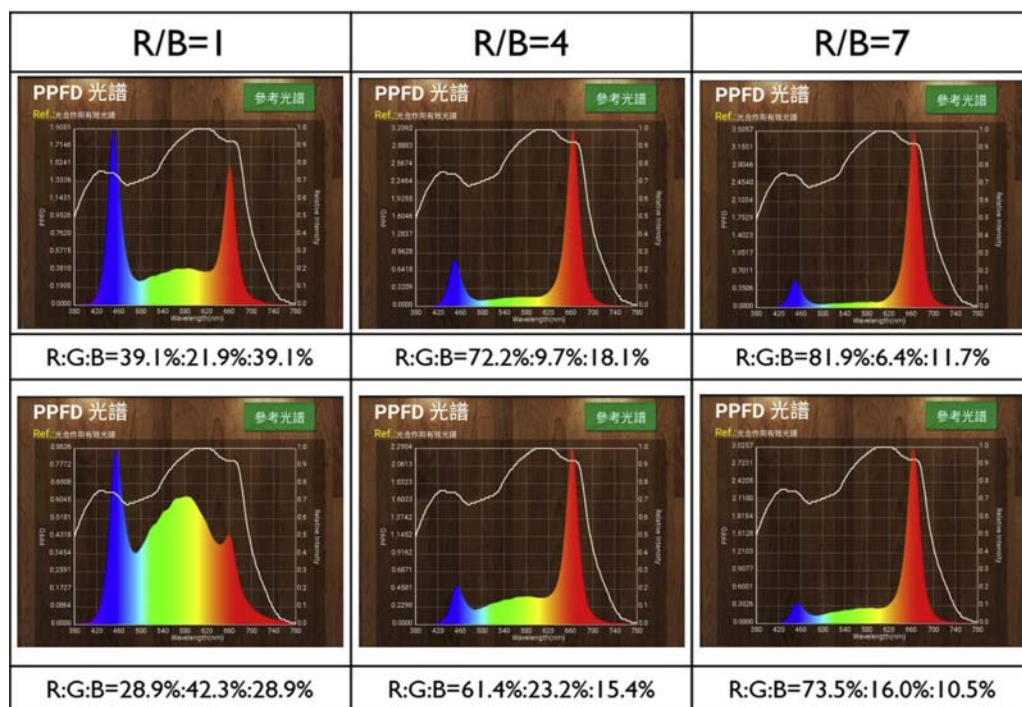


FIGURE 3.10

Spectra comparisons of “R/W/B adjustable” (upper 3) and “R/W adjustable” (lower 3) LED lamps at R/B ratios of 1, 4, and 7, from left to right, respectively. Included in the background is the McCree curve showing the photosynthesis response of green leaves.

Besides R/B, R/W, and R/W/B with adjustable spectra, we also developed R/FR LED lamps. The power of these lamps can be adjusted from 5 to 25 W per tube to provide different intensities. These are now commercially available from a local company in Taiwan.

UV and FR for phytochemical production and morphogenesis research

Ultraviolet (UV) light promotes phytochemical production in plants, particularly the UVA band, which ranges from 315 to 400 nm and the UVB band, which ranges from 280 to 315 nm. The UVC band (100–218 nm) should not be used for plant production. UVB is much more energy intensive compared with UVA, and thus needs to be used carefully. The dosage of UV should be calculated based on the similar concept of DLI (daily light integral, PPFD times the number of hours of light per day), that is, the dosage of UV equals the intensity multiplied by the duration of minutes for UVB and hours for UVA. Our UV application is aimed at the production of certain medicinal plants and red leaf lettuce.

Research on far-red light (FR, 700–800 nm) in controlled environments is a recent focus worldwide. Some studies have focused on the effects of end-of-day (EOD) treatment and others have focused on flower induction for ornamental plants. We are keen to inhibit the flowering of a local variety of spinach, which is a long-day plant. The heads will start flowering if the duration of light is longer than 12 h. The traditional way to prevent this in a controlled environment is through production

using 11 h of artificial light. In the plant factory, we hoped to provide a longer duration of light in order to improve the fresh market weight. Thus, we conducted research using FR to inhibit flowering, and the results were quite promising. We were able to provide 14 h of light with less than 10% flowering. The fresh weight was increased from 60 g per plant at 11 h using Cool White (CW) LEDs up to 160 g per plant at 14 h using CW LEDs and FR light.

Low-potassium lettuce production for ESRD patients

Patients with end-stage renal disease (ESRD) require hemodialysis as well as a careful diet, including low potassium intake. One of the major sources of potassium for an adult is vegetables (300 ppm or more for lettuce). Potassium (K) is one of the three macroelements (N, P, K) that plants need for healthy growth. Two companies, one in Japan and one in Taiwan, are producing low-potassium (less than 100 ppm) lettuce with the sacrifice of fresh weight (less than 60 g per plant). However, their production method involves replacing the potassium with sodium in the nutrient solution. The end product is low in potassium, but high in Na, which is also not good for patients with kidney disease or patients with high blood pressure or heart disease.

Some companies in Taiwan use the slogan “healthy salt” to promote their products, claiming only 50% salt compared with other brands. However, it is not widely known that they use KCl to replace NaCl, which is the same idea as above, replacing K with Na in the nutrient solution to produce low-potassium lettuce.

Instead of using Na to replace K, we used NH_4 in the solution, which produces lettuce that is not only low in potassium, but also low in sodium and nitrates without sacrificing too much of the fresh weight (Fang and Chung, 2018).

3.3.4 Business models of PFAL in Taiwan

The PFAL is attracting attention because it is new to the general public and its benefits attract environment- and health-conscious consumers. However, without a proper business model, cash problems could occur if not planned carefully. For the hardware installation, reliable engineering is needed; for the management of production, shipping, and handling, skilled workers are needed to ensure successful operations; for marketing and banking, financial success is critical. To achieve financial success, the manager should ask the following questions: How well will the products sell and at what price? How long will the products last without losing their value? What are the production and marketing risks?

Various business models are being tested in the Taiwanese market. The product can be the plant itself, such as in the form of a whole plant, loose leaves, or baby leaves. The product presentation is very important, such as the type of packaging: a sealed soft plastic bag, a soft plastic bag with tiny holes, or a sealed hard plastic box. Different packaging methods for different circumstances can be used for customers, with different costs. Is it a product that does not need to be washed before eating or is it just like the products grown in greenhouses? Emphasizing the fact that the product is locally produced instead of imported or transported from across the country is also important. Some fresh products can be provided with salad dressing, which must of course be tasty. Another simple feature is well-designed packaging bags and boxes to make the product more attractive than traditional agricultural products.

The sales channels can be membership based, through a website, within the company, or in the local community. It is important to limit the amount of sales through third parties. Selling the products through supermarket chain stores (owned by others) should only be a temporary practice because the

shelf charge is normally too high. For PFAL products, B2C (business to consumer) is much more favorable than B2B (business to business).

If the company is unable to sell all its products, another product line can be considered. One company in Taiwan developed more than 10 kinds of processed products using vegetable ingredients, including ice cream, egg rolls, bread, noodles, facemasks, skincare soap, etc. It can also be served as nutritional additives in various forms such as juice, powder, and tablets. Different kinds of vegetable additives have different prices for the same product. For example, noodles with butter lettuce and noodles with iceberg lettuce do not cost the same.

A construction company integrated the PFAL concept in their community construction plan. Each family will have a home appliance style device to grow vegetables at home and the community will have a service division providing seeds, seedlings, and stock nutrient solutions, etc. to community residents. A green life style is proposed.

Consider a shop or a restaurant that has a PFAL and sells fresh, local products. This is a popular business model in Taiwan. Such shops are normally chain stores and are located in various parts of the cities.

Several companies focus on the development and sale of the home appliance style plant production units and indoor green walls for home use. One company produces aquaponics units for hobby growers and homeowners.

Some companies construct PFALs for others, and most of them have a demo unit for potential customers to view. Successful companies usually have a demo unit at a more convincing scale, with daily production of no less than 100 plants and stable operation of at least several months. Established sales channels are needed. Unfortunately, few companies reach these requirements, which makes them less convincing.

Many PFAL-related hardware companies include those that supply LEDs, construct clean rooms, supply air conditioning systems, hydroponics systems, power supply, and thermally insulated materials. These companies started to build PFAL demo units and learned how to grow plants, all aiming to become a PFAL turnkey provider.

In short, there are several distinct business models in Taiwan:

1. PFAL production of leafy greens for own use. For example, restaurant owners and corporations with more than 1000 employees.
2. PFAL production of leafy greens for web customers and members. Some companies are quite flexible, and even exchange membership with other health-related organizations such as yoga clubs.
3. PFAL production of leafy greens and processed products with vegetable additives.
4. PFAL production of leafy greens as an attention-grabber but with other means of profit such as construction or chain-store sales of organic dry foods.
5. Home appliance-style PFAL module providers with a demo unit.
6. Home appliance-style PFAL module providers with alliances in the construction industry.
7. PFAL-related hardware providers that build PFAL demo units to sell their products and plan to become a turnkey provider.
8. PFAL turnkey builders and consultants with or without a PFAL demo unit.

As mentioned above, although the PFAL companies in Taiwan are small in scale, they are flexible and willing to try various business models. At present, some look promising and some have failed.

Even with the same business model, some companies are making a profit while others are losing money, the same as in any other emerging industry.

3.3.5 Conclusions

The PFAL industry is booming in Taiwan. Without financial and policy support from the government, private companies are highly interested and willing to become involved in this new industry. PFAL-related NPO organizations have been established, enabling the horizontal and vertical connection and integration of companies.

At present, there are no private agricultural organizations involved in PFALs in Taiwan. Several farmers' associations considered converting their unused warehouses to PFALs, but eventually dropped the idea. High initial cost is the first concern; finding a sufficient number of competent workers and managers to run the PFAL is another concern. Besides academic training in undergraduate and graduate schools in Taiwan, our team offers 30-hour and 18-hour workshops twice per year and once per season, respectively. So far, more than 900 people have been trained, but less than 10% actually entered the business afterward and less than 5% have an agricultural background. Training qualified managers and workers for the PFAL industry is a critical issue that needs to be addressed to enable worldwide business opportunities.

Many companies became involved with a view to the business opportunities of the turnkey projects. However, some have failed to prove that their system can efficiently grow quality plants. Unfortunately, some companies considered PFALs as a quick way to make money, leading to lawsuits and public confusion. So far, among all the international turnkey projects, around 15 PFALs have been built by Taiwanese PFAL companies, mostly in China and one in southeast Asia.

Some consumers have questioned the use of artificial lights and hydroponics, and 4 years ago there were complaints about the use of unnatural chemicals. Public awareness, food safety problems, environmental problems, and frequent media exposure of PFALs help consumers to learn, appreciate, and trust PFAL technology and products. Nevertheless, there is still work to be done, such as bringing down the cost, increasing the value, and increasing the number of suitable varieties to be grown in PFALs. PFALs can coexist with organic agriculture and traditional agriculture. PFALs could surely play a key role in urban agriculture and the modernization of our cities.

3.4 Korea

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3.4.1 PFALs, an icon of innovation in future production and consumption

One of the sectors frequently mentioned in the policy on the Fourth Industrial Revolution in Korea is smart farming. In the “Five-Year Plan to Incorporate the Fourth Industrial Revolution” pronounced in 2017, smart farming is one of the major parts along with smart medical services, smart factories, and smart transportation. The Korean government plans to invest a total of two billion US dollars (USD) by 2022 for developing related technologies. Information and communications technology (ICT) convergence and artificial intelligence-based farming business have also been considered as solutions

for addressing climate change, bringing a paradigm shift in agricultural production, and creating new engines of growth.

The Ministry of Agriculture, Food and Rural Affairs had announced that four smart farm innovation valleys (SFIVs) will be established by 2022. Sangju-si in Gyeongsangbuk-do and Gimje-si in Jeollabuk-do were chosen as the locations for the SFIVs. The master plans for the SFIVs proposed by the two consortia were approved and construction of the facilities will start in 2019. The SFIVs will be agriculture clusters based on ICT to promote mutual growth of the agricultural industry including PFALs and related sectors by nurturing young talent and promoting technological innovation.

The Korean government's "Plan for Promotion of Agri-Food and ICT Convergence" has been implemented since 2013 for the purpose of applying ICT technologies to the production, distribution, and consumption of agricultural products. One of its major projects currently being implemented is the supply of "Smart Greenhouse Systems," which supports the monitoring and control of plant cultivation environments via smartphones by providing high-tech sensing, monitoring, and control equipment to farms. As the most advanced farming system, PFALs have gained general acceptance as an ideal field for the successful application of the ICT-converged smart farming system. These policies and projects have been drawn up because PFALs are recognized as not only a promising export to foreign countries but also as a solution to the insufficient supply of leafy vegetables, especially in the hot and cold seasons.

3.4.2 Research and technical development (RTD)

Korea has developed various technologies for vegetable breeding, hydroponics, greenhouse structure, and hardware and software for controlling the environment in greenhouses, which can easily be diverted to vegetable production in PFALs. Even though many elemental technologies for PFALs have been developed and related research results published, commercialized PFALs were not introduced until 2009, while vegetable production in greenhouses has become crucial to the Korean horticulture sector. Universities and national and prefectural research agencies were the main agents for RTD in the area of controlled environment agriculture (CEA) that enables the grower to manipulate a cultivation environment to the desired conditions and is useful for isolating specific environmental variables for more precise studies in plant responses to modified environmental conditions. There is obvious commonality in research areas between PFALs and CEA with artificial lighting.

Prior to 2009, most practical research studies in PFALs or closed plant production systems (CPPSs) were performed using fluorescent lamps as the artificial lighting source. Some representative samples of related RTD in those days were CPPSs for producing plug transplants of seed-propagated vegetables for the nursery industry; CPPSs for producing vegetatively propagated strawberry transplants for consolidating the national proliferation program; CPPSs for producing Welsh onions as the raw material for an instant ramen company; and CPPSs for producing salad vegetables for restaurant chains, hamburger chains, and vegetable processing and distribution companies. Total solutions, which were developed for each system and delivered to the contracted enterprises, included the cropping system, cultivar selection, seed sterilization, seed germination, transplant raising, transplanting, planting density, temperature settings for air and nutrient solution, photo and dark period setting, PPF setting, harvest scheduling, and others.

The biggest change in RTD between pre- and post-2009 was the application of LEDs as the sole lighting source for PFALs. Physiological and morphological responses of plants grown under a red, blue, green, or even far-red monochromatic lighting source and under combinations of those monochromatic sources were studied mainly on a scientific basis from the late 1990s. Due to the low luminance and high cost of LEDs, however, they were not widely used as a lighting source for PFALs. Research and development of PFALs with LED lighting has progressed dramatically since 2009, mainly due to the government's "Development of major components for IT-LED-based plant factories" project adopted in that year. Four other major research projects funded by the government related to PFALs with LED lighting were "Development of LED-IT-based plant production techniques for environment-friendly horticultural products," "Development of lighting techniques using LED that has particular spectra promoting plant growth," "Commercialization for export of plant factories," and "Development of urban-type PFAL technology."

As various types of LED chips with different wavelengths and wattages and lighting fixtures with different shapes, combination of spectra, and luminance have become available on the market, research on PFALs with LED lighting has sharply increased not only at universities and public research agencies but also in private companies. The results of many studies on the photosynthesis, growth, and morphology of various vegetables responding to different PPF ratios of blue and red LEDs have been published in international journals as well as in domestic journals including *Horticulture*, *Environment*, and *Biotechnology* and *Horticultural Science and Technology* (official journals of the Korean Society for Horticultural Science), and *Protected Horticulture and Plant Factory* (official journal of the Korean Society for Bio-Environment Control). As the PFAL business has expanded worldwide, private companies have started accumulating their confidential research data on lighting equipment such as white LEDs having different spectra, productivity, cropping systems, cultivation methods, specialized quality, and even profitability. [Samsung Electronics Co., Ltd. \(2018\)](#), a world-leader in advanced digital component solutions, announced new horticulture LED lineups including full-spectrum packages and modules as well as monochromatic LEDs. As high-efficiency and cost-effective alternatives to higher-priced red LEDs, full-spectrum LEDs could help lower the costs of a grower's entire lighting system. [LG Innotek \(2018\)](#), a global specialized material and component manufacturer, also announced the launch of a set of LEDs for plant growth.

National research agencies have set up PFALs for research at the Antarctic King Sejong Station (55 m²) of the Korea Institute of Ocean Science; the National Academy of Agricultural Science (446 m² in Suwon-si and 1506 m² in Wanju-gun) of the Rural Development Administration (RDA); the Protected Horticulture Research Station (142 m² in Haman-gun) of the RDA; the National Institute of Horticultural and Herbal Science (55 m² in Umseong-gun) of the RDA; and the Korea Institute of Science and Technology (33 m² in Gangneung-si). Meanwhile, prefectural research agencies have also set up PFALs at the Agricultural Research & Extension Services of Gyeonggi-do (115 m² in Whaseong-si); Chungcheongbuk-do (413 m² in Cheongju-si); Gyeongsangbuk-do (132 m² in Daegu-si); and Gyeongsangnam-do (198 m² in Jinju-si), and universities have done so at Seoul National University in Seoul-si and Suwon-si; Chungbuk National University in Cheongju-si; Gongju National University in Yesan-gun; Gyeongsang National University in Jinju-si; Jeonbuk National University in Jeonju-si and Iksan-si; and Yenam University in Cheonan-si.

3.4.3 Private companies and farms in the PFAL business

As mentioned above, several private companies have started PFAL businesses since 2009 and currently about 40 companies are operating their PFALs for demonstration and/or production. Some of them have also set up PFALs for their customers in Korea including local cities and boroughs, agricultural research centers of local government bodies, universities and schools, cafés and restaurants, hospitals, shopping malls and department stores, community centers in apartments, farms, and others, as well as in other countries including Japan, China, Mongolia, and Qatar. Most of the companies that have built PFALs for research, demonstration, and/or production and are currently operating them can mainly be classified as small and medium-sized enterprises. These include Paru (20 m² in Suncheon-si), Insung Tec (165 m² in Yongin-si), Taeyoun Eco & Agro-Industry (165 m² in Seoul-si), KAST Agricultural System & Technology (132 m² in Gumi-si), Korea Refrigerated Foods (50 m² in Gimhae-si), Cham Farm (50 m² in Goseong-gun), Jinwon Farm (330 m² in Gwangju-si), Wise Control (33 m² in Yongin-si), Vegetechs (661 m² in Goyang-si), Future Green (50 m² in Suwon-si), Farm Eight (1314 m² in Pyeongtaek-si), Miraewon Farm (654 m² in Pyeongtaek-si), Agtonics (318 m² in Ulju-gun), Happy Enjoy Farm (200 m² in Gyeongsan-si), Maxfor (115 m² in Yongin-si), Alga FarmTech (33 m² in Paju-si), and Eum Farm (226 m² in Gimpo-si).

Companies classified as large-scale enterprises such as Dongbu Lightec (9 m² in Bucheon-si), Nongshim Engineering (230 m² in Anyang-si), Lotte R&D Center (17 m² in Seoul-si), and Pulmuwon (495 m² in Eumseong-gun) are operating PFALs mainly for research. In 2007, the Kyowon Group, also classified as a large-scale enterprise, established the “Wells Farm” PFAL (2314 m² in Paju-si) for producing transplants of various vegetables and herbs that are shipped to their rental contractors of indoor LED cultivators.

3.4.4 Achievements and challenges

PFALs and related industries in Korea have accomplished dramatic developments in a relatively short period of a few decades. A report from the RDA (Lee, 2014) estimated the annual market of the domestic PFAL business at about 577 million USD, and the added value from the PFAL business itself and industries with forward/backward linkages at about 77 and 500 million USD, respectively.

All the elemental technologies for PFALs have been successfully developed from a series of systematically designed joint research among multidisciplinary experts. In practice, the lighting technology for PFALs in Korea skipped over fluorescent lamps, and LED technology was directly applied, which caused problems such as high initial investment and difficulties in cultivation due to a lack of information. On the other hand, it has provided the Korean PFAL industry with a great opportunity to confidently compete with PFAL-advanced countries (Chun, 2014), especially the world-leading LED manufacturers in Korea who recently launched horticulture solutions as described above. Small home-use PFALs equipped with newly developed LEDs will soon be introduced by major home appliance manufacturers.

Policy support projects drawn up by the government were also effective for the early stage of PFAL development in Korea. Further investment by the private and public sectors is needed to ensure the stable growth of this industry by networking smaller PFALs to ensure successful marketing of their products and developing high value-added products to meet the various demands and health consciousness of an aging society. Unlike in Japan, the PFAL business in Korea is not subsidized by national or provincial governments. The PFAL industry will develop further if a subsidy program is introduced as PFAL-related technologies approach successful deployment on a commercial scale.

3.5 China

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3.5.1 Development and current status of PFALs in China

The first PFAL in China was built in 2002 for research mainly focusing on hydroponic technologies and their control systems, supported by the Ministry of Science and Technology of China. Thereafter, R&D on PFALs in China advanced rapidly. The first commercial PFAL was established in Changchun City, Jinlin Province, in 2009 and the first family-style mini-PFAL was exhibited at the Shanghai Expo in 2010. Since 2010, PFALs have become increasingly popular, mainly in large cities on the east coast. By 2013, about 35 PFALs were operating in Beijing, Shandong, Shanghai, Nanjing, Changchun, and Guangdong. The total estimated number of PFALs is now more than 200, and the number keeps increasing. With the development of PFALs, interest in the PFAL industry is spreading out from research institutes and protected horticulture companies to nonagriculture sectors, such as e-commerce (Jingdong, Tmall, Taobao), realty, the LED industry, etc.

3.5.2 Research activities

Since 2002, projects related to PFALs, such as hydroponic technologies, LED technologies, and the Internet of Things, gradually received support from the Chinese government. The National Advanced Science and Technology Project on Intelligent Plant Factory Production Technology (2013–17; 46 million yuan), led by the Chinese Academy of Agricultural Sciences (CAAS) and supported by the Ministry of Science and Technology of China, included participants from 15 universities, institutes, and companies. Improvements in the following key PFAL technologies were achieved: (1) energy-saving LED light source and intelligent light environment control; (2) equipment for multilayer cultivation systems; (3) energy-saving environmental control based on light and temperature coupling; (4) nutrient solution management and vegetable quality control; and (5) intelligent control systems based on network management. As a result of the project's achievements, the Ministry of Science and Technology of China supported the Science and Technology Partnership Program (2018–20), a joint project between China and Romania. In this project, the CAAS will establish a demonstration park at the University of Agronomic Sciences and Veterinary Medicine of Bucharest in Romania to export key technologies related to PFALs. Additionally, in 2017, the Ministry of Science and Technology of China granted a key National Research and Development Program of China (2017–20) on LED lighting in PFALs. Twenty-four universities, institutes, and companies joined this CAAS project.

3.5.3 Typical PFALs and case studies

To date, the PFALs in China have mainly been used for (1) scientific research in research institutes and/or universities, such as the CAAS, the Beijing Academy of Agriculture and Forestry Sciences, and

South China Agricultural University; (2) commercial application by companies (e.g., AgriGarden, AEssense, Kingpeng, Sanan Sino-Science); and (3) demonstration and education in high technologies.

Chinese Academy of Agricultural Sciences

Since 2002, researchers at the Institute of Environment and Sustainable Development in Agriculture (IESDA) of CAAS have been conducting studies on PFAL technologies. Starting in 2005, PFALs with fluorescent lighting, with half LED lighting, and with full LED lighting were consecutively built in the IESDA. In 2013, an LED PFAL with a floor area of 100 m² was built on the roof of the IESDA. Studies conducted in these PFALs mainly focused on technologies for energy saving, LED lighting, nutrient solution management, and vegetable quality control. In 2015, two experimental LED PFALs with a total floor area of 60 m² were built in the IESDA (Fig. 3.11). Ongoing studies in the PFALs include optimization of the lighting formula for various crops at different growth stages, and the addition of an electric field for improving the light use efficiency and the quality of leafy vegetables.

In 2016, two PFALs with a total floor area of 160 m² were built in a greenhouse complex at the demonstration center of CAAS (Fig. 3.12). The demonstration center, which is operated by Beijing



FIGURE 3.11

Inside view of PFAL labs built at IESDA of CAAS.

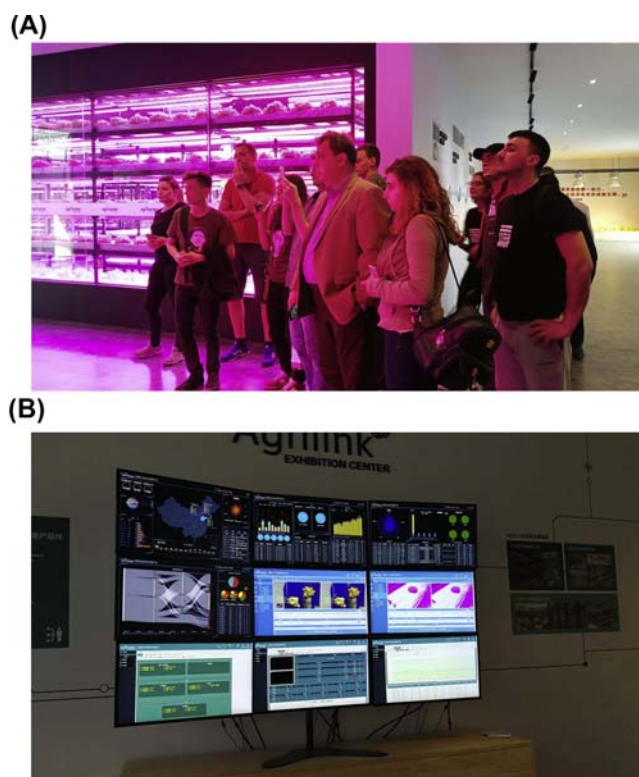


FIGURE 3.12

PFALs built in 2016 at the demonstration center of CAAS. Left: outside view of the demonstration PFAL, right: integrated environment control using IoT in the PFALs.

IIESDA Protected Horticulture Co., Ltd., has a total floor area of 4 ha divided into seven halls for exhibiting new PFAL technologies, new cultivation methods, and new ideas on urban, household, and/or office horticulture. A three-layer vertical farming model was recently built at the demonstration center. The underground layer is for mushroom production, and the middle and top layers are for leafy vegetable production under artificial light and fruit vegetable production under sunlight, respectively.

In 2016, the CAAS established the Institute of Urban Agriculture in Chengdu City, Sichuan Province. The planned construction area is 19 ha and the experimental area is 200 ha. Urban agriculture research center (12,000 m²) and Intelligent vertical agriculture exhibition center (5600 m²) will be built at this institute in 2019 (Fig. 3.13). Research related to urban agriculture mainly focuses on intelligent horticulture equipment, photobiology and cultivation with artificial light, vertical agriculture, functional and ornamental plant production, recycling of organic waste, plants and human health, and an innovation model for urban agriculture. The development of an internal leader research center in urban agriculture is expected in the near future.

FIGURE 3.13

Institute of Urban Agriculture, CAAS, in Chengdu City, Sichuan Province. Left: Layout of the institute, right: urban agriculture research center (12,000 m²) and intelligent vertical agriculture exhibition center (5600 m²) at the institute.

(A)**(B)**

Beijing research centre of intelligent equipment for agriculture, Beijing academy of agriculture and forestry sciences

The Beijing Research Centre of Intelligent Equipment for Agriculture at the Beijing Academy of Agriculture and Forestry Sciences (BAAFS) commenced research on PFALs in 2010. In 2014, a PFAL with spectrum-adjustable LED panels was built at BAAFS based on two 40-foot containers. In 2016, a PFAL with a floor area of 150 m² was built in the underground space of a greenhouse connected to the BAAFS (Fig. 3.14). The PFAL is characterized by its high-precision adjustable LED light source and control system.

The research conducted at the BAAFS mainly focuses on quality control technologies for leafy vegetables, energy-saving technologies for lighting, and lighting formulas based on the photo-physiology of plants. Studies have been carried out on plant species exposed to different light spectra (monochromatic or mixed red, blue, yellow, green, infrared, and white) and different light supply modes (continuous, alternating, intermittent, and gradient lighting). The response mechanism of plants to the light environment at different growth stages, energy consumption, and light energy use efficiency were analyzed in this PFAL. The experimental plants included leafy vegetables, medicinal vegetables, and fruit vegetable seedlings.



FIGURE 3.14

External view of PFAL labs built in 2016 at BAAFS.

South China agricultural university

In 2017, the South China Agricultural University constructed an experimental LED plant factory with a total floor area of 150 m² that includes six layers for leafy vegetable cultivation and seven layers for a seedling nursery (Fig. 3.15). This plant factory is operated by a research team studying controlled-environment horticulture. The research topics are functional vegetable production (e.g., higher anti-oxidant content vegetables) by combined light environment and nutrient solution. The experimental varieties in this PFAL are lettuce (more than 10 lettuce cultivars), Brassica leafy vegetables (pak choi, choy sum, Chinese kale, kale), baby leaf greens, and microgreens.

AEssense

AEssense is a high-tech Chinese company based in Silicon Valley with its headquarters in Shanghai. It was founded in 2014 and is engaged in intelligent PFAL/vertical farming and Internet of Agricultural Things systems. In 2015, AEssense built a PFAL with a floor area of 1200 m² for high-tech demonstrations and scientific research in Shanghai (Fig. 3.16). The company integrates sensors and precision automation software with an aeroponics platform to provide a complete solution for PFALs, including IoT-based, modular, scalable, intelligent, and data-driven growth systems for the expanding indoor agriculture market. It also operates a subscription-based service providing fresh, pure, and safe produce in China, using AEssense plant growing systems, certified as compliant with the highest food safety standards.

Beijing Kingpeng international hi-tech corporation

Beijing Kingpeng International Hi-Tech Corporation is a leading greenhouse manufacturer, operating as a subsidiary of the Beijing Agriculture Machinery Institute (BAMI). In 2010, Kingpeng built a PFAL with a total area of 1300 m² (Fig. 3.17). The PFAL includes a tissue culture room, seedling room, artificial light culture room with a solar electrical energy generation system, and a vegetable storage room.

FIGURE 3.15

PFAL labs built in 2017 at the South China Agricultural University for producing lettuce (more than 10 lettuce cultivars), brassica leafy vegetables (pak choi, choy sum, Chinese kale, kale etc.), baby leaf greens, and sprouts.

**FIGURE 3.16**

PFALs built in 2015 by AEssense in Shanghai City. Left: lettuce grown with LED lighting, right: aeroponics systems developed by AEssense.

(A)**(B)**

(A)



(B)

**FIGURE 3.17**

PFAL built in 2010 by Beijing Kingpeng International Hi-Tech Corporation. Left: exterior features of the PFAL, right: interior features of the PFAL.

The company built the Beijing Plant Engineering Technology Research Center with a total area of 22.7 hm² located in Tongzhou Song Town in the suburbs of Beijing. The center is used for scientific research, production, and hi-tech demonstrations. Kingpeng is engaged in professional PFAL and greenhouse research, design, manufacture, installation, sales, and after-sales service. Kingpeng has sold its services related to protected horticulture (e.g., plant factories) to more than 30 provinces in China and about 30 countries abroad.

Sanan sino-science

Fujian Sanan Sino-Science Photobiotech Co., Ltd. is a venture company cofounded in 2015 by the Fujian San'an Group and the Institute of Botany, Chinese Academy of Sciences. Based on the advantages in plant sciences of the Institute of Botany, CAS and the LED technical advantages of the Fujian San'an Group, Sanan Sino-Science carries out research, integration, and demonstrations in the areas of plant lighting, bioengineering, development, and utilization of natural compounds, pharmaceutical intermediates, and intelligent equipment.

FIGURE 3.18

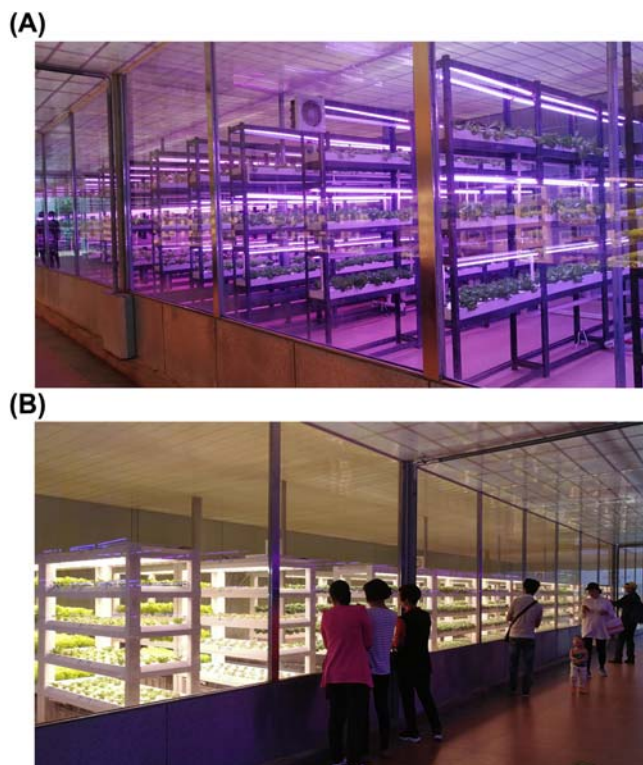
PFAL built in 2016 by Sanan Sino-Science for leafy vegetable production.



In 2016, Sanan Sino-Science established its first PFAL with a total floor area of 3000 m² and a cultivation area of 10,000 m² for leafy vegetable production with a daily production of 15,000 plants (Fig. 3.18). In 2017, Sanan Sino-Science built another PFAL for medicinal plant production with a total floor area of 5000 m². At the same time, a leafy vegetable PFAL with a total area of 10,000 m² was built in Las Vegas in the USA. The company also exports their PFAL-related services to other countries. Thus, Sanan Sino-Science is expected to become an international leader in PFAL production, demonstration, and dissemination of information and technologies.

Shouguang

Shouguang City in Shandong Province plays an important role in the development of protected horticulture in China. The China International Vegetable Fair is held in Shouguang every year from April 20 to May 30, drawing more than 2 million visitors. New technologies for protected horticulture are exhibited at the fair. An LED PFAL (40 m²) was first exhibited at the 10th China International Vegetable Fair in 2009. Millions of visitors were attracted to this new plant production system. The area of the PFAL was expanded to

**FIGURE 3.19**

PFAL in Shouguang City for an exhibition.

200 m² in 2010 and to 400 m² in 2017 for the 11th and 18th China International Vegetable Fair, respectively. New energy-saving technologies of LEDs, hydroponics, multicultivation of fruit vegetables and leafy vegetables, and intelligent control systems were demonstrated at the PFALs (Fig. 3.19).

3.5.4 Conclusion

PFALs have been developing rapidly in China, especially since 2010. In the past several years, the Ministry of Science and Technology of China has provided financial support for several projects aimed at the development of PFALs. Key technologies from China are exported abroad. Private companies in other sectors, such as e-commerce (Jingdong, Tmall, Taobao), realty, and the LED industry are enthusiastically entering the PFAL industry. The establishment of PFAL-related NPO organizations, such as the China National Intelligent Plant Factory Innovation Alliance, enables the horizontal and vertical connection and integration of companies. Thus, due to the support and enthusiasm from various aspects, the number and functions of PFALs in China keeps increasing. There is no doubt that PFALs will play a key role in urban agriculture in major cities in China.

3.6 Thailand

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3.6.1 R&D on PFALs in Thailand

R&D on PFALs in Thailand began in the early 2000s with medicinal herbs and leafy vegetable production in hydroponic systems supplemented with artificial light in semiclosed buildings equipped with air conditioners. In the early period, fundamental research was conducted to understand the plant responses to a controlled environment for two types of crops, tropical/subtropical species and temperate species, which cannot usually be grown outdoors in the Thai climate. Since 2015, PFALs have become well-known and popular, and government and national funding agencies started funding research studies on PFALs. Several universities and research institutes have conducted research on plant production in PFALs, both basic and applied. Moreover, innovative technologies have also been developed for light sources, sensors, control systems, database services, mobile applications, insulators, and cooling systems for PFALs.

The PFAL project at the Mahidol University Faculty of Science started in 2002. The mini PFAL model “Plantopia” received the second-place award at the Thailand Innovation Awards (Fongsirikul and Supaibulwatana, 2003). Thereafter, research mainly focused on understanding the effects of an artificial environment on the growth and metabolomics of medicinal plants. Specifically, the effects of both aerial and root zone environments (such as light spectrum, light intensity, photoperiod, CO₂ concentration, nutrients, etc.) on physiological and morphological responses, growth, and particularly on bioactive compounds, were investigated in several species (Supaibulwatana et al., 2011; Cha-um et al., 2011). Some of these studies were in collaboration with Chiba University, Japan (Maneejantra et al., 2016; Joshi et al., 2017). Around the same time, a group of scientists from the Mahidol University Faculty of Science developed many automated devices including robots, drones, and sensors for application to PFALs and precision agriculture (Wongchoosuk et al., 2013, 2014a, 2014b; Subannajui et al., 2012). At the Mahidol University Kanchanaburi Campus, another PFAL project started in 2005 on growing high-value leafy vegetables in a hydroponic system. In 2016, several start-up companies, funding agencies such as the NIA (National Innovation Agency), Super Cluster Initiative, and STEM Workforce of the NSTDA (National Science and Technology Development Agency) and the ARDA (Agricultural Research Development Agency) toward the Thailand 4.0 project, and Mahidol University formed a collaborative team to conduct research on cultivation systems, lighting systems, control systems, nutrient supply schedules, and cloud-based applications for PFALs. In 2018, Mahidol University and Chiba University established the MU-CU PFAL Research and Training Center. The main purpose of this joint unit is to build pilot models of PFALs, shipping

**FIGURE 3.20**

Model PFAL in a trailer container at Kanchanaburi Campus of Mahidol University.

containers, and mobile PFALs for producing high-value leafy vegetables and medicinal herbs on an industrial scale (Fig. 3.20)

Maejo University is one of the leading agricultural institutions in northern Thailand. PFAL research at Maejo University started in 2012 in cooperation with Ameriseed International Co., Ltd. in order to reduce the limitations of petunia seed production in Thailand, which can only be efficiently produced once a year in winter in highland areas (Sakhonwasee et al., 2017; Phansurin et al., 2017). Optimizing the light parameters, nutrient solution, CO₂ concentration, and air circulation in the PFAL successfully achieved year-round production with the capacity to produce 50,000 high-quality seeds per m² in one cropping period of 4 months. Maejo University and Ameriseed International also plan to use PFALs to accelerate breeding programs for petunias and other flower crops (Fig. 3.21).

Kasetsart University, another leading agricultural institution, also uses the principles of PFALs in fundamental research. In 2018, a mini-PFAL and a shipping container type PFAL were developed by the Faculty of Engineering, Kasetsart University Chalermphrakiat Sakon Nakhon Province Campus to facilitate research on plant phenotyping using an artificial intelligence approach. The plant growth and development of orchids and medicinal herbs under LED lights during each production stage are continuously investigated in a simple system at the Faculty of Horticulture (Fig. 3.22). In 2018, KAPI (Kasetsart Agricultural and Agro-Industrial Product Improvement Institute) received a grant to build

**FIGURE 3.21**

PFAL for petunia seed production at Maejo University, Thailand.



FIGURE 3.22

PFAL at Chulalongkrajit Sakon Nakhon Province Campus of Kasetsart University, Thailand.

two 8×8 m PFALs in Bangkok for producing high-quality plants as raw materials for use in the cosmetics industry.

The KMUTT (King Mongkut's University of Technology Thonburi) Faculty of Engineering started a PFAL project in 2015 on the system design of household PFALs. In 2016, they grew strawberries using a hydroponic system installed in an insulated room inside a building. In 2018, with financial support from the NSTDA, the School of Bioresources and Technology at KMUTT started a PFAL project related to sprout production for Thai medicinal herbs.

As the leading research institute of Thailand, BIOTEC (under NSTDA) working with Chiba University initiated a project by developing a prototype PFAL under the Innovative Program for Sustainable Agriculture funded by the government. This PFAL consists of (1) a production unit with a production area of 690 m^2 (4 rows $\times$ 4 tiers $\times$ 1.2 m width $\times$ 36 m length) and (2) three research units with a production area of 225 m^2 . The total floor area is 600 m^2 . Four hydroponic systems are equipped with LED lights of adjustable light intensity and spectrum under a controlled environment. Other facilities such as an automatic transplanting robot and rooms for transplant production, harvesting, extraction, and bioactive compound detection are also available (Fig. 3.23).

BIOTEC has also built a model-type community-scale PFAL for medicinal herb production and technology transfer in local medicinal herb production. The container-type PFAL has a floor area of 56 m^2 and is equipped with eight-tier production shelves (1.2 m width $\times$ 6.0 m length $\times$ 5.4 m height) and LED lighting. This model was first implemented in Nakhon Phanom Province on a commercial scale for the production of medicinal herbs through cooperation by the government and the private sector. As a funding agency, the NSTDA also financially supports two research clusters and programs of the KMUTT and KU Kamphaeng Sean Campus. Moreover, the Government Pharmaceutical Organization under the Ministry of Public Health is interested in growing cannabis in a closed-type PFAL in a building with a floor area of 1100 m^2 .

3.6.2 R&D and business in the private sector

From the trend of PFALs in Thailand, more than 10 small and medium-sized start-up companies employed PFALs to boost their plant production and production efficiency and to avoid pesticide residues and unpredictable climate changes. The most popular crops grown in PFALs are leafy vegetables and herbs containing nutraceutical substances. Several companies are expected to use

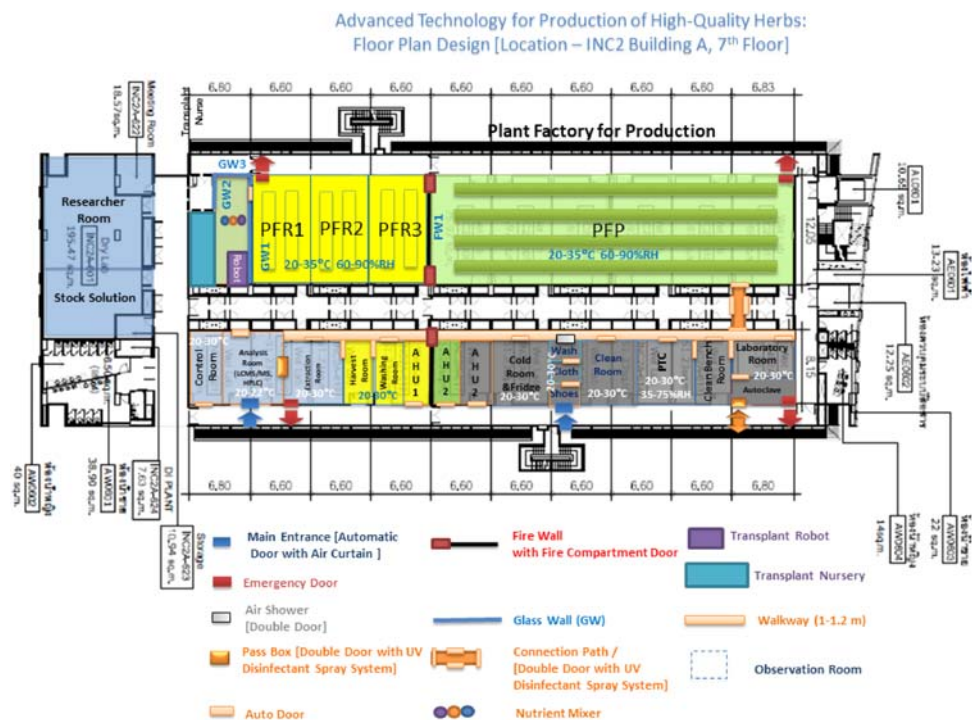


FIGURE 3.23

Floor plan of PFAL at BIOTEC, NSTDA (National Science and Technology Department Agency), Thailand launched in March 2019. In the floor plan, PFR and PFP denote, respectively, PFAL for research and PFAL for production.

PFALs for producing high-quality ethnic vegetables for export to countries around the world. Some companies in the light and lamp business have also started planning for R&D of LEDs for plant production applications and sensors for measuring and monitoring PFAL environments to better control the growth and quality of produce from PFALs.

Growlab Agritech (Thailand) Co., Ltd. started their business in 2010, producing indoor hops under a specially designed LED lighting system that provides the required levels of humulone alpha acid and lupulone beta acid. Growlab Agritech was the first company sponsored by the National Innovation Agency (NIA) for the development of PFALs. Mahidol University is a mentor of this project in designing the PFAL lighting system (Fig. 3.24).

Agro Intelligent Co., Ltd. (AI), a leading company in PFALs, was established in 2015 in Bangkok, Thailand. AI has two main businesses: "Plant Factory and Smart Agriculture" and "Research and Development." Regarding the first one, AI aims to create new innovation for plant factories and smart agriculture mainly on the construction and control system. The on-demand construction design, lighting, and control system are being tackled in collaboration with Hanmo Co., Ltd., Japan; the research and development business involves collaboration with Mahidol University, the National Innovation Agency, the Thailand Research Fund, Hanmo Co., Ltd., and Nekkoya Inc. AI has developed several household



FIGURE 3.24

PFAL for research developed by Growlab Agritech Co. Ltd., Thailand.

PFALs, the GROBOT model with a fully controlled environment for plant growth, such as temperature, light, CO₂ concentration, and nutrient solution, for residents living in urban areas including educational functions. This model can be connected and controlled via the Internet with a built-in data logger. GROBOT X, with an IoT-based design for the touch screen panel controlled via a smart device through the Internet, was established in October 2018 in collaboration with Hanmo of Japan (Fig. 3.25).

Due to the rainy season, outdoor year-round production of high-quality organic vegetables is not possible. In Wangree Resort, Nakhon Nayok, a private sector company, built a PFAL with a floor area of 100 m² in 2018 for growing leafy vegetables (<https://www.youtube.com/watch?v=eO8J9VfQpsQ>). In a PFAL, the same vegetables as well as other leafy imported vegetables can be successfully grown with a much shorter production time.

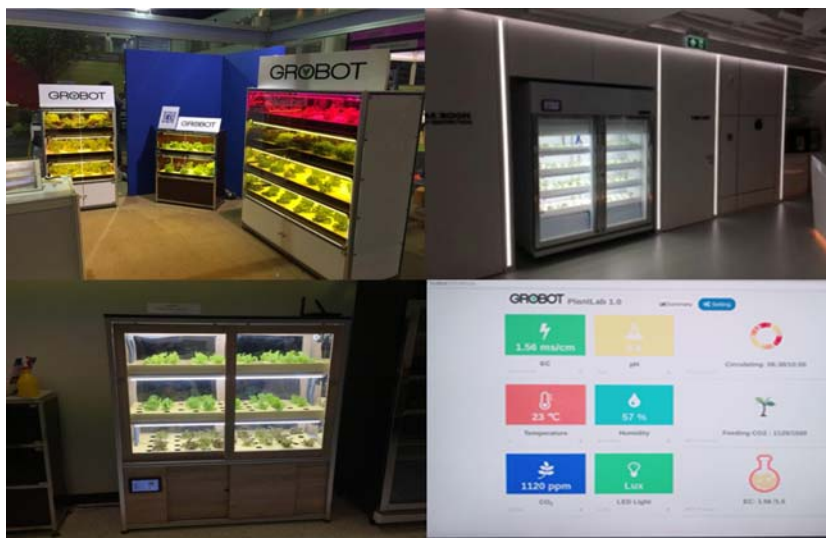


FIGURE 3.25

PFAL model GROBOT with user interface and touch screen panel controlled via a smart device through Internet. (<http://www.growlaboratory.com/>).

3.6.3 Policy and future prospects for PFALs

The Thai government's Ministry of Science and Technology launched a policy of using advanced technology for strengthening the agricultural sector. PFALs are considered one of the target frontier technologies to support the bioeconomy scheme for national development under the "Thailand 4.0" project via the EECd and EECi platforms. The EECi site at Wang Chan Valley is owned by PTT Public Company Limited (a petroleum company) and is located in Tambon Payupnai, Wang Chan District, Rayong Province, and covers about 3000 rai (480 ha). BIOPOLIS, a center for research and innovation in life sciences and biotechnology at Wang Chan Valley, focuses on the development spanning several industrial groups encompassing the bioenergy industry, biochemicals and bioplastics, and the nutraceutical, biomedical, and biopharma industries under the bioeconomy scheme pertaining to the current agricultural base of Thailand. The PFAL was chosen as a strategic technology for the production of high-value crops.

3.7 North America

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3.7.1 History

The United States introduced PFALs for crop production in the 1980s. Those earlier facilities were producing leafy crops using a hydroponic system under high-intensity discharge (HID) lamps inside a building. Among them, a commercial lettuce production facility located in Dekalb (west of Chicago) in Illinois operated for many years before its closure in the early 1990s. Then over the past several years, coinciding with the increasing interest in local food production, as described in a later section, large commercial PFAL facilities were built within close proximity to mega cities (such as Chicago and New York). In addition to large facilities, smaller PFALs were developed nationwide based on shipping containers and targeting the local market for fresh leafy greens.

In the early 2000s, production of plant-made pharmaceuticals (also known as molecular farming) became a viable application of PFAL. In fact, a few large-scale commercial facilities were built in the US and Canada to produce pharmaceutical protein products (antigens and antibodies) using genetic modification or transient expression of plants. Over the past 10 years, many states in the US legalized production and use of cannabis (*Cannabis sativa*) as an alternative medicine, while it is still controversial and against the federal laws; these "new crops" have been produced in highly controlled production systems (including greenhouses and PFALs). Furthermore, recreational use of cannabis is now legal in Canada and several states in the US. Due to the extremely high value of cannabis, these production facilities are typically equipped with various state-of-the-art technologies, serving as the main driver for introducing new and modern technologies in commercial plant production.

In addition, as a unique application, a small PFAL was developed to produce fresh vegetables in the US South Pole Station. This 22 m² footprint facility produced over 30 different types of crops (several at

FIGURE 3.26

A new type of business of leasing small stand-alone PFAL production units together with crop maintenance services. The photo shows a project of Farmshelf (www.farmshelf.com) in a cafeteria at the Grand Central Station in New York City.



one time) including tomatoes, lettuces, and herbs for the crew year-round (Patterson et al., 2012). The facility also has an adjacent room (9 m²) separated by a glass wall for research station personnel to experience the bright plant growing environment. This human psychological support by providing green plants was critical in such an isolated environment as the South Pole. PFAL industries also experienced diversifications including unique business models such as providing stand-alone growing systems together with complete services to manage crops in various food businesses such as restaurants and cafeterias (Fig. 3.26). Yet, as in the nature of new industries, some companies have already closed, suggesting the need for supporting the sustainable development of this newly emerging industry.

3.7.2 Contribution of space science

It should be noted that many key technologies employed in plant growing systems in PFAL originated from the US. The most significant technological contributions are hydroponics/soilless culture technique and use of light-emitting diodes (LEDs) for plant production. Hydroponic systems were invented as a research tool of plant nutrition and later implemented as a leafy crop production system to provide fresh vegetables for US troops stationed on several islands in the western Pacific during World War II (Jones, 2000) and in Japan to provide fresh and clean vegetables for the military personnel and their families after World War II. Around 1980, the US National Aeronautics and Space Administration (NASA) initiated its Controlled Ecological Life Support System (CELSS) Program (Wheeler, 2004), where plants were grown hydroponically under artificial (electric) lighting. Maximizing crop productivities while minimizing electric power use was a key focus area in NASA's life support research. As a result, much research was conducted focusing on developing lighting technologies. An efficient lighting system based on LEDs was first developed for NASA's life support applications by a group of scientists and engineers in Wisconsin (Bula et al., 1991). Much of our current knowledge regarding light quality requirement originated from the outcome of many research groups in US land-grant institutions funded by NASA. For example, the necessity to add a small amount of blue light to red light was first reported by Bula et al. (1991) followed by others, establishing the general understanding of light qualities required to grow plants using monochromatic light sources.

3.7.3 Current status and future prospects

As of 2017, there were reportedly more than 30 PFALs for food production in the US (Kerslake, 2017), nearly four times greater than that reported in 2015. There were also more than 100 shipping container growers (Kerslake, 2017) and several vendors for “turn-key” growth containers in the US. Compared with the status of the US and Canada, Mexico is considered at a very early stage of technological introduction with only a few commercial trials currently being examined in Mexico City (K. Garcia, personal communication). In Sonora, Mexico, one company is producing microgreens for the local market.

Most PFALs in North America are growing lettuce in various forms (e.g., mature full heads, mini heads, and baby greens), and other leafy greens including kale, arugula, and culinary herbs in forms of baby and microgreens. Basil is a widely grown crop in PFALs and sold as fresh-cut leaves, microgreens, or living plants (with roots attached). For baby and microgreens, mixing selected leafy greens to develop “ready-to-eat” salad mixes with various flavors (e.g., “Asian mix” or “spicy mix” with selected brassica species) is unique in North America. Microgreens of selected leafy green species are widely grown in PFALs. This is because microgreens are generally high value with limited shelf life and therefore well suited for this type of production system. Baby greens and microgreens definitions are often vague, but generally microgreens are at the beginning of first true leaf expansion and baby greens include a few true leaves. Some facilities are certified organic producers and/or implement aquaponics. While the percentage of market share of leafy greens from PFALs is still negligibly small, some PFALs in North America have ventured into diversifications of crops including fruiting crops such as tomato, cucumber, and strawberry.

For transplant production, there is at least one company producing grafted tomato seedlings using PFAL. Applications of PFALs for transplant production of other plant species have been slowly experimented with and one company in Pennsylvania built a PFAL to produce young plants of various culinary herbs to grow and finish in greenhouses. This combination of PFAL and greenhouse seems to be very successful and applications for more different vegetable and ornamental species can be expected in the coming years.

Regarding facilities, many of these utilize a multitiered production system with LED lamps installed in each tier. The distance between tiers is relatively tall (~ 1 m) compared with what is commonly seen in Japan and other Asian countries, presumably primarily considering logistics (accessibility to the plants) and assuring air circulation around the plants, despite the low space-use or energy-use efficiency. Hydroponic systems (NFT or shallow water culture with recirculation system for nutrient solution) are typical and some NFT channels are designed to use in a vertical orientation to enhance space use. Many PFALs use repurposed warehouses instead of constructing new buildings. While CO₂ enrichment is a common practice in containerized growth rooms, it is not a common practice when voluminous warehouse buildings are used. Such buildings often have air-handling systems with minimum ventilation to assure human health and the growing space is often shared with CO₂-emitting workers who are engaged in activities such as transplanting, harvesting, mixing nutrient solution, etc. As a result, the CO₂ concentration inside the growing facility is, anecdotally, not at problematic low levels such as we may experience in a truly contained environment. However, the benefit of CO₂ enrichment to compensate the DLI (daily light integral) requirement should be more recognized among PFAL growers.

More technological improvements are necessary to make the PFALs more productive and profitable. One such critical area is an HVAC optimization especially for humidity management (N. Sabeh,

personal communication) and lighting optimization. For the latter, many US horticultural scientists now work on innovative lighting technology development for increasing productivity and produce quality. Issues of humidity management became problematic along with the introduction of efficient LED lighting that results in a lower cooling demand (and thereby a lower degree of dehumidification) in the production system, compared with older lighting technologies. With highly efficient LEDs, growers experienced high relative humidity (sometimes more than 90%) during the day, and had to use additional power for dehumidification to achieve 60%–70% relative humidity in order to avoid fungal disease outbreaks. Ventilation may be an easy way to release the moisture (when outside absolute humidity is lower than inside). The design recommendation to minimize the ventilation rate, in order to maintain the high CO₂ use efficiency (e.g., Yoshinaga et al., 2000) needs to be reevaluated. As CO₂ cost is far less expensive than electricity (to achieve the same amount of yield increase), it may be worth considering having minimum ventilation to release the moisture rather than maximizing CO₂ use efficiency, at least until low-cost technological innovation becomes available for humidity management. Assuring ventilation capacity is also critical when air quality issues exist. For some cases, identifying and eliminating problematic sources of causing VOC (volatile organic compound) accumulation is challenging and some literature in fact recommends ventilation as high as 12 times per hour (e.g., Tibbitts, 1996). Brassica species are particularly sensitive to specific VOC (symptoms can be seen at less than 1 ppb) (Tibbitts, 1996) and can be a good index crop to detect VOC injuries associated with problematic PFAL designs.

One prominent trend among the commercial PFALs in North America may be the strong support from retailers (grocery stores) that promote local food production and organic produce. The traditional supply chain of fresh vegetables and fruits in North America is driven by a small number of large-scale produce industries with a limited number of open-field production regions. For example, California (most seasons) and Arizona (in winter) together supply more than 90% of the lettuces and other leafy crops consumed in US and Canada. Postharvest technology is critical for such a nationwide supply chain as it takes up to 5 days to transport the produce using refrigerated trailers. Finding a 2-week-old “fresh” head of lettuce in grocery stores is not unusual in North America. Also, while this type of supply chain contributes to lowering the production costs, it is prone to large outbreaks of foodborne illness. In 2018, there were a couple of multi-state outbreaks of *E. coli* O157:H7 bacteria in romaine lettuce produced in California and Arizona open fields, infecting hundreds of consumers. The first outbreak was due to the use of contaminated canal water used in an outdoor production field (CDC, 2018). For the second outbreak, the US Centers for Disease Control and Prevention (2018) made a blanket recall for all romaine lettuces and their products (such as salad) from of all markets nationwide. While this recall was unfair to PFAL and greenhouse growers (who were obviously not the cause of a nationwide outbreak), it gave opportunities for them to make the public aware of hydroponic technologies. Historically, most greenhouses and PFALs have not actively advertised the fact that their produce, for example, is grown under a modified or artificial environment without soil or sunlight, presumably due to the typical public perceptions being resistant to “high technologies” used in food production. Of interest, after the *E. coli* outbreak, the FDA made a recommendation of voluntary labeling a harvest location and a harvest date, as well as production methods such as hydroponically or greenhouse-grown (FDA, 2018). This may lead to wider recognition of hydroponics and controlled environment technologies and may accelerate the further expansion of the market of leafy greens grown in greenhouses and PFALs. Fresher and safer produce is expected to continuously attract North American consumers.

With this fast-growing status of PFALs and other types of controlled environment agriculture (CEA), it is critical to increase the academic research capacity to support this emerging industry sector. Forming industry associations catalyzing industry–academia collaborations may help but the competitive nature of venture capital in North America often makes communication among businesses more challenging. A grassroots effort has been initiated to exchange scientific communications as well as networking (CEPPT, 2018). Another crucial role of academia can be providing opportunities of education and training for those PFAL practitioners and planners. While such training and education for greenhouse crop production are available through various universities and supporting industries, those specific to PFALs are still limited in North America. Increasing the number of online course opportunities in the area of controlled environment agriculture may help meet such needs.

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Vertical farming in Europe: present status and outlook

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4.1 Introduction

Despite the name “plant factory” used in this book, and more generally in Asia, such a name is uncommon in European countries. Instead, “vertical farm” is the preferred term when referring to intensive plant production systems with vertically stacked or vertically inclined shelves (Den Besten, 2019). People living in cities tend to show criticism and low levels of acceptance for innovative forms of urban agriculture with connotations of intensive or high-tech agriculture, not consistent with the conventional and traditional picture of horticultural production (Benis and Ferrão, 2018; Sanyé-Mengual et al., 2016; Specht et al., 2016b, 2016a). Therefore, the popularity of the term “vertical farm” might be correlated with the fact that the European consumers favor the term “farm” rather than “factory” for association with fresh products. Some others (Benis and Ferrão, 2018) use the term “zero-acreage farming” (ZFarming) to refer to types of urban agriculture that don’t use farmland, and also includes low-tech alternatives. Other names that are commonly used are “city farm” or “indoor farm.” When (soilless) cultivation techniques are integrated with building climate control, the term “building-integrated agriculture” (BIA) is also used (Benis and Ferrão, 2018; Caplow and Nelkin, 2007). Vertical farms using skyscrapers for intensive food production in closed growing systems can also be referred to by the synonymous term “skyfarm” (Benis and Ferrão, 2018; Germer et al., 2011). In this chapter we use the term “vertical farm,” or similarly “indoor farm,” for all cultivation systems of plants in buildings without the direct use of solar light. This can include multiple stacked layers or single layers; systems may range from very small mobile systems that, for instance, fit in a kitchen up to large-scale production farms (Table 4.1).

The number and size of vertical farms in Europe is at present still rather small, but in recent years they have experienced rapid expansion. There are increasing investments and a concurrent proliferation of start-ups. Following a global trend, the expansion of this industry is mainly due to the simultaneous drop in the price of LED lighting technologies and the growing consumer demand for fresh, healthy, and local produce grown with limited inputs. Furthermore, the vacant office buildings that arose after the global financial crisis of 2007–08 fostered the process (Spruijt et al., 2015). In addition to producers, the supply industry for vertical farming has also expanded exponentially; this includes many start-up companies as well as established supply companies from the greenhouse industry.

Table 4.1 Typologies of vertical farms present in Europe.

Typology	Description
PFAL (plant factory with artificial light)	Vertical farming production system located in devoted space in an industrial building
Container farm	Shipping container equipped with self-contained vertical farming systems
In-store farm ^a	Vertical farming unit located at the place of consumption or purchase (i.e., supermarkets, restaurants)
Appliance farm ^b	Plug and play indoor growing system targeted for in-home and office use

^{a,b} In Asia, the terms micro- and mini-PFAL, abbreviated mPFAL in both cases, are also used to refer to appliance farm and in-store farm.

The cost-effectiveness, scalability, and environmental sustainability of intensive vertical farming are still uncertain (Benis and Ferrão, 2018). The initial investment per square meter of cultivation for a vertical farm can be up to 10 times higher than that of a high-tech greenhouse (Rabobank, 2018). Rabobank (2018) estimated the total operational costs per square meter of cultivation as two and a half to five times higher than that of a Dutch greenhouse. They estimated that, at present, the cost price per unit product is approximately twice that of lettuce grown in a Dutch greenhouse. As the cost price of produce from vertical farming is relatively high, the added value of vertical farming products needs to be high as well, in order to be cost-effective. This added value can be generated by a better product (better or more consistent quality, residue free, freshness, etc.) and a good marketing concept. Vertical farming companies often sell their vegetables at a premium, in some cases in line with the market prices of organic products (Benis and Ferrão, 2018). However, unlike in the United States of America, soilless-grown crops cannot be certified as organic in the European Community (European Commission, 2008; OTA, 2019).

The expansion of vertical farming has boosted research on controlled environment agriculture from which the existing greenhouse horticulture industry also benefits. Greenhouse vegetable producers often have established relationships with food distributors and are high-efficiency operators. Therefore, they may compete with vertical farms, instead of complement, for the same market, especially in regions or countries with a high concentration of greenhouses, like the Netherlands. Despite vertical farming companies often claiming to be “environmentally friendly” the actual sustainability of vertical farms is still under review by scientific researchers, and it appears to be site- and case-specific (Benis and Ferrão, 2018; Stanghellini et al., 2019). However, according to Graamans et al. (2018), currently in

the European area, greenhouses are more efficient in terms of purchased energy when compared to vertical farms, due to the vertical farms' high use of artificial lighting. Moreover, with vertical farming being an emerging industry, the quick and cost-effective implementation of a vertical farming project often conflicts with the need to comply with the local regulation and building codes (Benis and Ferrão, 2018).

4.2 Vertical farming nonprofit sector associations

Currently, in Europe, there are two international nonprofit industry associations for vertical farming: the Association for Vertical Farming (AVF) and the Farm Tech Society (FTS) (AVF, 2019; FTS, 2019). The FTS focuses on controlled environment agriculture (CEA) industry, of which vertical farming is a subgroup, while the AVF focuses on vertical farming only. There are also industry associations active in supporting vertical farming on the national level (e.g. the Association Française d'Agriculture Urbaine Professionnelle, UK Urban AgriTech Collective, UK Controlled Environment Users' Group) (AFAUP, 2019; CEUG, 2019; UKUAT, 2019).

Both the AVF and the FTS are supporting and fostering the vertical farming industry. Their main objectives are to provide an international network for professionals, establish standards, and advocate for policies to facilitate the growth of the vertical farming industry. Besides these, they work on the development of industry-certified vocational training for professionals whose ambition is to work in vertical farming.

4.3 The entrepreneurial landscape

4.3.1 Overview

As vertical farming is a young, capital-intensive sector, the most profitable way of utilizing vertical farming technology has yet to be fully established. Vertical farming companies exhibit a wide range of applications, both in terms of business and production models. Furthermore, most companies position themselves as technology providers rather than growers. In Table 4.1, the types of vertical farming production models (PFAL, in-store farm, container farm, and appliance farm) that have appeared on the European market are described.

The emerging cannabis production market might present itself to be a unique case, as the large profit margin justifies the companies' choice to turn to production in vertical farms. The legislation with respect to medical cannabis has been modified, or is under discussion, in some European countries (e.g., Denmark, Germany, Luxemburg, Malta, the Netherlands, the United Kingdom). Moreover, the cultivation and marketing of cannabis strains with lower cannabinoid THC content have been legalized for recreational use in Italy and Switzerland and have caused significant entrepreneurial excitement.

The European vertical farming industry is a market full of potential, but it is not without its risks. In 2018 and 2019, for example, a group of early-stage ventures and start-ups managed to get substantial investments and expand their market. A number of established companies, from supermarket chains to home and office furniture firms, also entered the vertical farming business. At the same time, multiple other companies faced financial problems and, in some cases, went bankrupt.

4.3.2 Examples for each vertical farming typology

PFAL

A PFAL of significant size (5120 m²) was constructed by Jones Food Company in North Lincolnshire, England (Fig. 4.1). This vertical farm has been in operation since autumn 2018 with some of the production sold to Greencore, an Irish convenience food producer (Abboud, 2019; Hortidaily, 2018a). Once it has reached its full capacity, the farm will produce up to ~400 tons of leafy greens annually, making use of advanced robotics. The implementation of this large-scale project was made possible by a partnership with the US company Current, a subsidiary of General Electric, which supplied 12.3 km of LED light bars. Between 2018 and 2019, Jones Food Company had raised part of its funding from both Guinness Asset Management and Ocado, a British online supermarket (Ocado, 2019). The vision of Jones Food Company is to continue opening vertical farms in the UK and abroad (Abboud, 2019).

Container farm

Agriool (Paris, France) is a start-up vertical farming company with a media presence. The company, founded in 2015, develops container farms for the cultivation of strawberries using aeroponics (Fig. 4.2). The total capital raised by the company over the period 2015–18 amounted to €37M (Crunchbase, 2019a; Dillet, 2018). At the start of 2019, Agriool had five container farms in operation in Paris, and began their global expansion in Dubai, with one container farm (Dillet, 2018).

In-store farm

Founded in 2013, the Berlin-based start-up Infarm develops in-store farms for retailers and restaurants to produce herbs, leafy greens, and microgreens (Fig. 4.3) directly on site. In total, Infarm has already raised about €120M from investors over the period 2013–19 (Crunchbase, 2019b). As of August



FIGURE 4.1

The PFAL of Jones Food Company in North Lincolnshire, England.

Picture Credit: Holly Challinor.

**FIGURE 4.2**

A container farm of Agricoool in Paris, France.

Picture Credit: Agricoool.

2019, the company was present in more than 350 in-store retail and distribution centers in Germany, France, Switzerland and Luxemburg harvesting more than 150,000 plants a month. The international expansion of Infarm was made possible by their partnership with more than 25 major retailers (e.g. Edeka, Metro, Migros, Casino, Intermarche, Auchan, Selgros and Amazon Fresh) (P. Kalaitzoglou, personal communication, August 7, 2019).

Appliance farm

Founded in 2009, Click & Grow is an Estonian start-up that develops appliance farms, or as described by the company: “smart indoor gardens” (Fig. 4.4). The EU is Click & Grow’s second largest market, after the United States of America. In October 2018, Click & Grow raised US \$11M, bringing the total funding for the company up to US \$17.9M (Click & Grow, 2018; Crunchbase, 2019c). The last investment round brought with it new strategic partners: Seb, the French world’s leader in small household equipment, Ikea, and Y Combinator, a top-ranked US start-up accelerator (Konrad, 2017).

In Table 4.2, a list of the European vertical farms producing herbs and leafy vegetables is presented.

The list does not include technology suppliers [e.g., Agrilution (Germany), Aponix (Germany), Aquapioneers (Spain), Citycrop (Greece), Evergreen farm (Norway), Fresh Square (Germany), Heragreen (Italy), Hexagro Urban Farming (Italy), Ingrin (Slovenia), La Grangette (France), Natufia (Estonia), Planthive (Belgium), Onefarm (the Netherlands), Ponix-systems (Austria), Prêt à Pousser (France), Refarmers (France), Robonica (Italy), Tomato+ (Italy), Urbanfarm (Ireland), Yard (Germany)]. A number of established companies supplying technology is described in Section 4.3.5.



FIGURE 4.3

An in-store farm of Infarm in the Metro's store in Paris, France.

Picture Credit: Metro.



FIGURE 4.4

An appliance farm of Click & Grow.

Picture Credit: Click & Grow.

Table 4.2 Examples of vertical farming companies in Europe. The vertical farming sector is highly dynamic and the authors do not pretend that this list is complete.

Name	State	Website
PFALs		
B-Four Agro	The Netherlands	http://www.b4agro.nl/
Byspire	Norway	http://www.byspire.no/
CityFarm Stockholm	Sweden	http://www.stadsbondens.se/
Deliscious	The Netherlands	http://www.deliscious.eu
Duurzame kost	The Netherlands	http://duurzamekost.nl/
Farmers Cut	Germany	http://www.farmerscut.com/
Future Crops	The Netherlands	http://www.future-crops.com/
Grönska Stadsodling	Sweden	http://www.grönska.se/
Grow Bristol	United Kingdom	http://growbristol.co.uk/
Growing Underground	United Kingdom	http://growing-underground.com/
Growx	The Netherlands	http://www.growx.co/
Growup Urban Farm	United Kingdom	http://www.growup.org.uk/
Hydropousse	France	http://www.hydropousse.fr/
Incifarms	Norway	http://www.incifarms.com/
Jones Food Company	United Kingdom	http://www.jonesfoodcompany.co.uk/
Jungle concept	Portugal	http://www.jungle.bio/
Robbe's Little Garden	Finland	http://robbes.fi/
Tasen Microgreens	Norway	http://www.tasenmicrogreens.no/
Tuinderij Bevelander	The Netherlands	http://www.tuinderijbevelander.nl/
Urbanika Farms	Poland	http://www.urbanikafarms.com/
Urbanoasis	Sweden	http://www.urbanoasis.life/
Van Namen Specialties	The Netherlands	http://www.vannamenspecialties.nl/
Vitro Plus	The Netherlands	http://www.vitroplus.nl/
In-store farms (restaurants)		
De Zusters (with Vaversa)	The Netherlands	http://www.dezusters.nl/
Emma (with Light4Food)	The Netherlands	http://emmarestaurant.nl/
Good Bank (with Infarm)	Germany	http://good-bank.de/
Restaurant of the Future (with Vaversa)	The Netherlands	http://vaversa.com/
Suncraft (with Hydrogarden)	United Kingdom	http://www.suncraft.co.uk/
The Green House (with Hrbs.)	The Netherlands	http://www.thegreenhouserestaurant.nl/

Continued

Table 4.2 Examples of vertical farming companies in Europe. The vertical farming sector is highly dynamic and the authors do not pretend that this list is complete.—cont’d

Name	State	Website
In-store farms (retailers)		
Auchan (with Agricooltor)	Italy	http://auchan-retail.com/
Auchan (with Infarm)	Luxemburg	http://auchan-retail.com/
Coop Butiker & Stormarknader (with Grönska Stadsodling)	Sweden	http://www.coop.se/
Edeka (with Infarm)	Germany	http://www.edeka.de/
Casino (with Infarm)	France	http://www.groupe-casino.fr/
Jumbo (with Own Greens)	The Netherlands	http://www.jumbo.com/
Metro (with Infarm)	Germany, France	http://www.metrogroup.de/
Migros (with Infarm)	Switzerland	http://www.migros.ch/
Container farms		
Agricool	France	http://agricool.co/
Ikea (with Bonbio and Urban Crop Solutions)	Sweden	http://www.ikea.com/

4.3.3 A deeper look into the Dutch vertical farming landscape

In the last few years, the Netherlands has been the site of great entrepreneurial activity related to vertical farming. Plantlab, founded in 2010, was one of the first companies in the Netherlands focused on developing concepts and cultivation strategies for vertical farming. Research is also conducted for partners in the field of breeding and production. Growx is a PFAL founded in April 2016. The company is located in a warehouse in Amsterdam and supplies herbs, microgreens, and baby leaves to the local catering industry, with a special focus on fine dining restaurants. The start-up capital (about €2M) was financed by two investment funds dedicated to “green” Amsterdam and the Netherlands. After initial success, in 2018 Growx experienced financial troubles and appointed new management. A new investment round is expected for 2019 (Nils, 2018). In 2018, in the village Hoenzadriel, the company Van Namen Specialties converted a mushroom nursery in a 160 m² vertical farm (Tiersma, 2019). Van Namen Specialties sells its herbs under the brand name Pika Surpresa to local restaurants and a supermarket. It is worth mentioning that Urban Farmers (The Hague), Europe’s largest rooftop greenhouse, declared bankruptcy in 2018, although according to the definition used in this chapter it is not considered a vertical farm (Sijmonsma, 2018). The bankruptcy followed that of its Swiss mother company located in Zurich. The Dutch branch of the company was active from May 2016. Urban Farmers combined greenhouse horticulture with aquaponics to produce ~30 vegetable crops and tilapia fish. Approximately 50% of the revenue came from guided tours of the greenhouse and catering for events (Küsterling, 2018). Its proximity to the Dutch region of Westland, a territory well known for its high concentration of highly efficient greenhouses, may have contributed to its failure. Nevertheless, also in

Westland, Future Crops, a large-scale vertical farm, arose. According to the information on their website, the company makes extensive use of automation, gets part of its energy requirements from 16,000 solar panels installed on the roof and has 8000 m² of potential cultivation space, which would make it, de facto, the largest vertical farm in Europe at present, and among the biggest in the world.

The use of vertical farming might in particular be successful when used for the cultivation of just a portion of a crop's life cycle. As reported by [Den Besten \(2019\)](#), Tuinderij Bevelander utilizes a vertical farm to assist in the year-round production of chives. The chives are seeded and grown in open fields during the first year and the bulbs are harvested in autumn when they lose the aerial portion. After a cold period of 3 months, a multilayer system supplied with artificial lighting is used to grow new leaves, that are ready for sale in 8 days ([Tuinderij Bevelander, 2019](#)). Several tulip producers are using vertical farming solutions for the forcing of the bulbs ([FloralDaily, 2016](#)). Deliscious uses a seven-layer system (>5000 m) under LEDs for the raising of young lettuce plants ([Deliscious, 2019](#); [Den Besten, 2019](#)). Subsequently, the plants are transplanted into a greenhouse, to complete the growth. The same approach is utilized for the cultivation of lettuce by B-Four Agro ([Tiersma, 2019](#)). Vitro Plus also uses vertical farming to cultivate plants in the early stage of development ([Vitro Plus, 2019](#)). Vitro Plus has 75% of the market share of the global fern industry and produces and sells ferns from tissue culture and spores using a multilayer system equipped with LED lighting, over a total of 6000 m². Micropropagation in combination with vertical farming is in fact a common and long-established practice for propagating young plants, in particular ornamentals.

4.3.4 Projects expected to be completed in the near future

Vertical farming is a fluctuating, dynamic new sector, characterized by the bankruptcy of several companies, as for instance Plantagon (Sweden) in 2019 or Urban Farmers (the Netherlands) in 2018, and the starting or expansion of others ([Sijmonsma, 2019, 2018](#)). Here we give examples of companies that have concrete plans to build or expand their vertical farms. In 2019, the Staay Food Group plans to construct a large-scale vertical farm next to their fresh convenience food factory, located in one of the Dutch polders, where fresh-cut fruit and vegetable salads are made ([Staay Food Group, 2019](#)). According to their initial plan, the vertical farm should have been completed in June 2017; however, this did not happen due to a number of delays including legislative issues regarding growing plants in buildings and acquiring subsidies. Seven Steps To Heaven (Eindhoven, the Netherlands) already possessing a 150 m² PFAL on the seventh floor of an old Philips power plant, will construct a food production farm of 2500 m² in 2019 for the production of leafy vegetables and herbs and also high-wire tomato, cucumber, and pepper crops ([Seven Steps To Heaven, 2019](#)). In Brussels, Belgium, Urban Harvest is building a large-scale vertical farm, which is due to be operational in 2019 (A. Van Deun, personal communication, February 4, 2019). In Milan, Italy, the start-up Planet Farms runs a 60 m² vertical farming research lab. They plan to build a large-scale PFAL between 2019 and 2020. Once completed, the vertical farm will be fully automated and able to produce ~1000 tons of leafy greens annually over a total cultivation area of ~10,000 m² (L. Travaglini, personal communication, August 6, 2019). Strategic partners of this project are Signify (Philips Lighting), Woodbeton (an Italian company specialized in large wood structures), Sirti (an Italian company specialized in large telecommunications networks), 255 Hec (an Italian supplier of turnkey plant and machinery and provider of knowledge process outsourcing), Repower

(a Swiss company operating in the energy business), Netafim (an Israeli manufacturer and distributor of irrigation and crop management technologies) and Travaglini, (an Italian manufacturer of climate control equipment and industrial automation for cured meat, fish, and cheese) (Fresh Plaza, 2019).

4.3.5 Examples of vertical farming as a new market for established European companies

The increasing importance of the emerging vertical farming industry has not gone unnoticed among established companies in search of opportunities for growth. Historical players in the greenhouse industry are expanding into vertical farming as a strategy for market development, identifying new users for current products. Similarly, companies previously strangers to the world of horticulture are rapidly expanding into the vertical farming sector.

Signify, the new company name of the Dutch manufacturer of light sources Philips Lighting, has been active in developing knowledge in the vertical farming sector, which they refer to as “city farming.” Their ambition is to become a leading supplier for an industry whose future success highly depends on lighting technologies (Signify, 2019). They have two research and demonstration facilities: Brightbox in Venlo (NL), in collaboration with Botany and HAS University of Applied Sciences, and the Philips Growwise Center in Eindhoven (NL). Many more European lighting companies are active in the field of vertical farming (e.g., Bjb, Bssled, Fiberli, Genesis Scientific, Heliospectra, Hortilux Schröder, Osram, Pj Industries, Prolite, Sanlight, Valoya). Several European vegetable breeding companies have also started to show interest (e.g., Basf, Bayer, Cn seed, Enza Zaden, Keygene, Rijk Zwaan) (Den Besten, 2019). In the area of automation and climate control solutions for greenhouse horticulture, many companies have adapted their technology for vertical farming (e.g., Bosman Van Zaal, Cambridgehok, Certhon, Codema, Cogas, Hoogendoorn, Idromeccanica Lucchini, Logiqs, Priva, Ridder). A consortium of Dutch companies launched the Urban Farming Partners which will build a large vertical farm in Singapore (Urban Farming Partners, 2019). In June 2019, Priva, Ocado, and the US-based vertical farm 80 Acres Farms started Infinite Acres, a joint-venture to provide a full-service solution for automated turn-key vertical farms (Infinite Acres, 2019).

As vertical farming seems to become a promising trend for applications in homes and offices, large European companies operating in the furniture sector have been showing interest. As of 2018, as already mentioned, Seb is cobranding with, and a distributor partner of, the Estonian start-up Click & Grow, in addition to being an investor. Ikea has also invested in Click & Grow. In 2016, Ikea launched a vertical farming kit to hydroponically grow herbs and leafy greens with artificial light (Ikea, 2019). Furthermore, in 2017 and in 2019, they invested in the well-known US vertical farm Aerofarms. During events dedicated to art and design, the Ikea’s innovation lab, Space10, proposed innovative furniture concepts based on vertical farming (Caspersen, 2018; Space10, 2019, 2018). Ikea announced that it will present a new series of indoor farming products for households to encourage a sustainable lifestyle in 2019 (Yalcinkaya, 2018). The products will be in stores by 2021. At the beginning of 2019, Ikea installed two container farms next to its stores in Helsingborg and Malmö (Sweden) to grow lettuce for its restaurants (Hortidaily, 2019; Thomasson, 2019). The container farm systems that grow plants using a nutrient solution produced from organic waste have been developed by Bonbio, a Swedish circular farming company, and Urban Crop Solutions, a Belgian vertical farming technology supplier. Another example of a company operating in the furniture sector showing interest in appliance farms is the Italian company Comprex. Jointly with the University of Bologna, Riviera (designer and manufacturer of household electrical appliances) and

Flytech (designer and producer of custom lighting products), Comprex is developing a small hydroponic system that allows for setting crop species-specific features with reference to light, climatic condition, and irrigation management (F. Orsini, personal communication, January 13, 2019).

A number of food service providers are installing in-store farms on their premises. The aim is to become self-sufficient in providing herbs and microgreens and to offer fresh and clean products. In addition, in-store farms serve as entertainment for customers. In Berlin, Germany, the restaurant Good Bank grows the salad leaves for its menu next to the counter using Infarm's in-store farms. In Bristol, United Kingdom, the restaurant Suncraft has an in-store farm developed by Hydrogarden. In Utrecht, the Netherlands, The Green House has a rooftop greenhouse equipped with artificial light and vertical farming units provided by Hrbs. The rooftop greenhouse serves as an eye-catching showcase and a producer of herbs for the customers. In Eindhoven, the Netherlands, the restaurant/bar/patisserie Emma grows its leafy greens using an in-store farm provided by the company Light4food. On the campus of Wageningen University and Research, the Restaurant of the Future produces part of its leafy greens using a vertical farm unit provided by Vaversa, a company focused on producing in-store farms for restaurants. At the start of 2019, Vaversa has 10 units throughout the Netherlands and is collaborating with Sodexo, a French food services and facilities management company (Sodexo, 2018). Vaversa started a pilot unit with the fine dining restaurant De Zusters in Maarsen (O. Francescangeli, personal communication, February 4, 2019).

To serve the increasing customer demand for fresh healthy produce, with a sustainable story and a small ecological footprint, big players of the European retail industry started testing in-store vertical farming concepts. The German company Metro is one of the biggest retails and wholesalers in Europe. In 2016, partnering with Infarm, Metro launched a pilot project to grow on-site herbs and vegetables in its wholesale store in Berlin (Maxwell, 2016). In late 2018, as a sign that the Berlin experience was beneficial, they inaugurated a new 80 m² in-store farm in Metro's main shop in Paris (O'Hear, 2018). In November 2018, the French mass-retail Casino also implemented an Infarm unit in its store in Varenne Saint-Hilaire (Cadoux, 2018). Edeka, the largest German supermarket corporation, has introduced in-store farms to 71 points of sale across Germany, in cooperation with Infarm. Likewise, Migros, Switzerland's largest retail company, has introduced seven Infarm in-store farms in shops across Switzerland (Infarm, 2019). Jumbo, among the Netherlands' largest supermarket chains, started its first in-store farm in the town of Veghel, in December 2018: the multilayer hydroponic system was developed by the Dutch company Own Greens (Jumbo, 2018). Again, in December 2018, the Belgian retail corporation Colruyt announced its plan to introduce in-store farms in autumn 2019 to offer fresh and sustainable herbs under its own label Boni Selection (Hortidaily, 2018b). Starting from October 2018, the Swedish supermarket chain Coop Butiker & Stormarknader has initiated a collaboration with the vertical farming start-up Grönska Stadsodling to grow herbs directly in stores (Coop, 2018). Also in 2018, the French international retail Auchan introduced in a hypermarket in Madrid, a hydroponic set-up to provide customers with fresh lettuce for purchase (Hortidaily, 2018c). Furthermore, Auchan, together with the Italian start-up Agricooltur, is testing an aeroponic in-store farm in one of its hypermarkets in Italy (Souissi, 2019). In 2019, Auchan placed some of Infarm's in-store farms in one of its stores in Luxemburg (Sawers, 2019). The strategic approach of Auchan to indoor farming market was reflected by the investment of Creadev—the private equity fund of the founders of the Auchan—in Gotham Greens, a famous US urban greenhouse company (Burwood-Taylor, 2018).

4.4 Final remarks and conclusions

Vertical farming is still an up-and-coming sector with room for improvement. Although the number of companies within this industry is currently relatively small in Europe, it is attracting many companies willing to invest. The most profitable way of capitalizing on vertical farming technology has yet to be established. It is too early to make any far-reaching conclusions on the market success of the vertical farming industry in Europe. It is important to reduce the cost price of the products and energy use in the coming years. The crops grown are, in many cases, leafy vegetables and herbs. However, there is also some diversification with crops such as strawberry and tomato. Vertical farming might also be well suited for production of plants with specific metabolites, for use as pharmaceuticals, nutraceuticals, or skin care products. Aside from companies focusing on vertical farms as simply the production of plants in specialized facilities, there is an interesting trend of companies utilizing the vertical farming concept in other ways such as in-store farming in restaurants and supermarkets, and appliance farms supported by companies operating in the furniture sector.

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Plant factory as a resource-efficient closed plant production system

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List of abbreviations

COP	coefficient of performance for cooling
CPPS	closed plant production system
CTPS	closed transplant production system
EC	electrical conductivity of nutrient solution
FL	fluorescent lamp
LAI	leaf area index
LCA	life cycle assessment
LED	light-emitting diode
PAR	photosynthetically active radiation
PFAL	plant factory with artificial lighting
RUE	resource use efficiency
SPPS	sustainable plant production system
VPD	water vapor partial pressure deficit

List of symbols, variable and coefficient names, units, and equation numbers

A_A (MJ m ⁻² h ⁻¹)	Electricity consumption of air conditioners (heat pumps) (Eqs. 5.9, 5.11, and 5.12)
A_L (MJ m ⁻² h ⁻¹)	Electricity consumption of lamps (Eqs. 5.8, 5.11, and 5.12)
A_M (MJ m ⁻² h ⁻¹)	Electricity consumption of water pumps, air fans, etc. (Eqs. 5.11 and 5.12)
A_T (MJ m ⁻² h ⁻¹)	Total electricity consumption ($A_A + A_L + A_M$) (Eq. 5.11)
CUE	CO ₂ use efficiency (Eq. 5.3)
COP	Coefficient of performance of heat pumps for cooling (Eqs. 5.9 and 5.12)
C_{in} (μmol mol ⁻¹)	CO ₂ concentration of room air (Eqs. 5.4 and 5.13)
C_{out} (μmol mol ⁻¹)	CO ₂ concentration of outside air (Eqs. 5.4 and 5.13)
C_L (μmol m ⁻² h ⁻¹)	CO ₂ loss to the outside (Eqs. 5.3 and 5.4)
C_P (μmol m ⁻² h ⁻¹)	CO ₂ fixed by plants (Eqs. 5.3 and 5.13)
C_R (μmol m ⁻² h ⁻¹)	CO ₂ released in room air by human respiration (Eqs. 5.3 and 5.13)
C_S (μmol m ⁻² h ⁻¹)	CO ₂ supplied to room air from CO ₂ cylinder (Eqs. 5.3, 5.7, and 5.13)
D (μmol m ⁻² h ⁻¹)	Dry mass increase rate of plants (Eqs. 5.5 and 5.6)
EUE_L	Electric energy use efficiency (Eq. 5.7)
F (m ²)	Floor area of culture room (Eqs. 5.13, 5.14, 5.16, and 5.17)

f (MJ kg ⁻¹)	Conversion factor from plant dry mass to chemical energy, 20 MJ kg ⁻¹ (Eqs. 5.5–5.7)
FUE _I	Inorganic fertilizer use efficiency (Eq. 5.10)
h	Conversion factor from electric energy to PAR _L (Eqs. 5.7 and 5.8)
H_h (MJ m ⁻² h ⁻¹)	Heat energy removed from culture room by heat pumps (Eqs. 5.9 and 5.12)
H_V (MJ m ⁻² h ⁻¹)	Heat energy exchange by air infiltration and penetration through walls (Eq. 5.12)
I_{in} (mol mol ⁻¹)	Ion concentration of “I” in nutrient solution at the inlet of culture beds (Eq. 5.17)
I_{out} (mol mol ⁻¹)	Ion concentration of “I” in nutrient solution at the outlet of culture beds (Eq. 5.17)
I_S (mol m ⁻² h ⁻¹)	Supply rate of inorganic fertilizer ion element “I” supplied to the PFAL (Eq. 5.10)
I_U (mol m ⁻² h ⁻¹)	Absorption rate of inorganic fertilizer ion element “I” by plants (Eqs. 5.10 and 5.17)
k_C (kg m ⁻³)	Conversion factor from volume to mass of CO ₂ (1.80 kg m ⁻³ at 25°C and 101.3 kPa) (Eqs. 5.4 and 5.13)
k_{WV} (kg m ⁻³)	Conversion factor from volume to mass of water (0.736 kg m ⁻³ at 25°C and 101.3 kPa) (Eq. 5.2)
k_{LW} (kg m ⁻³)	Conversion factor from volume to mass of liquid water (997 kg m ⁻³ at 25°C and 101.3 kPa) (Eq. 5.16)
LUE _L	Light energy use efficiency with respect to PAR _L (Eqs. 5.5 and 5.7)
LUE _P	Light energy use efficiency with respect to PAR _P (Eq. 5.6)
N (h ⁻¹)	Number of air exchanges (Eqs. 5.2, 5.4, 5.13, and 5.14)
PAR _L (MJ m ⁻² h ⁻¹)	Photosynthetically active radiation emitted from lamps (Eqs. 5.5, 5.7 and 5.8)
PAR _P (MJ m ⁻² h ⁻¹)	Photosynthetically active radiation received at plant community surface (Eq. 5.6)
V_A (m ³)	Volume of room air (Eqs. 5.2, 5.4, 5.13, and 5.14)
V_{LW} (m ³)	Volume of nutrient solution in culture beds (Eqs. 5.16 and 5.17)
X_{in} (kg m ⁻³)	Water vapor density of room air (Eqs. 5.2 and 5.14)
X_{out} (kg m ⁻³)	Water vapor density of outside air (Eqs. 5.2 and 5.14)
W_C (kg m ⁻² h ⁻¹)	Liquid water collected for recycling use in the PFAL (Eqs. 5.1 and 5.14)
W_L (kg m ⁻² h ⁻¹)	Water vapor loss rate from the PFAL to the outside (Eqs. 5.1 and 5.2)
W_P (kg m ⁻² h ⁻¹)	Water held in plants in the PFAL (Eq. 5.1)
W_S (kg m ⁻² h ⁻¹)	Liquid water supply rate into the PFAL (Eqs. 5.1 and 5.15)
W_T (kg m ⁻² h ⁻¹)	Transpiration rate of plants in the PFAL (Eqs. 5.14 and 5.15)
W_U (kg m ⁻² h ⁻¹)	Water uptake rate of plants in culture beds in the PFAL (Eqs. 5.15 and 5.16)
W_{in} (kg m ⁻² h ⁻¹)	Water inflow rate to hydroponic culture beds in the PFAL (Eqs. 5.16 and 5.17)
W_{out} (kg m ⁻² h ⁻¹)	Water outflow rate from hydroponic culture beds in the PFAL (Eqs. 5.16 and 5.17)
WUE	Water use efficiency (Eq. 5.1)

5.1 Introduction

This chapter describes the characteristics and principal components of a plant factory with artificial lighting (PFAL), which is one type of closed plant production system (CPPS). Then, the concept and definition of resource use efficiency (RUE) are described for each resource component. The characteristics of the PFAL are compared with those of a greenhouse, mainly from the viewpoint of RUE. It is shown that the use efficiencies of water, CO₂, and light energy are considerably higher in the PFAL than in a greenhouse. On the other hand, there is much room for improvement in the light and electric energy use efficiencies of the PFAL. Challenging issues for the PFAL and RUE are also discussed. This chapter is an extended and revised version of Kozai (2013c).

5.2 Definition and principal components of PFAL

A PFAL, a type of CPPS, is defined as a warehouse-like structure covered with opaque thermal insulators, in which ventilation is kept at a minimum, and artificial light is used as the sole light source for plant growth (Kozai, 1995, 2005). In a PFAL, the environment for plant growth can be controlled as precisely as desired, regardless of the weather. In addition to the recirculating nutrient solution in a hydroponic system, the water transpired by plants can be condensed and collected at the cooling panel of air conditioners and then recycled for irrigation. Closed transplant production systems and closed micropropagation systems are two kinds of PFAL (Kozai et al., 2000, 2005).

A PFAL consists of six principal structural elements (Fig. 5.1): (1) a thermally well-insulated and nearly airtight warehouse-like structure covered with opaque walls; (2) a multitier system (mostly 4–16 tiers or layers; about 40–60 cm vertically between tiers) equipped with lighting devices such as light-emitting diodes (LEDs) over the culture beds; (3) air conditioners (also known as heat pumps), principally used for cooling and dehumidification to eliminate heat generated by lamps and water vapor transpired by plants in the culture room, and fans for circulating air to enhance photosynthesis and transpiration and to achieve a uniform spatial air distribution; (4) a CO₂ delivery unit to maintain CO₂ concentration in the room at around 1000 $\mu\text{mol mol}^{-1}$ (or ppm) during the photoperiod for enhancing plant photosynthesis; (5) a nutrient solution delivery unit; and (6) an environmental control unit including electrical conductivity (EC) and pH controllers for the nutrient solution (Kozai, 2007; Kozai et al., 2006).

A PFAL must be designed and operated to achieve the following goals: (1) maximize the amount of useable or salable parts of plants using the minimum amount of resources; (2) maintain the highest RUE; (3) minimize pollutants released into the environment; and (4) minimize costs while achieving the previous three goals (Kozai, 2007; Kozai et al., 2006).

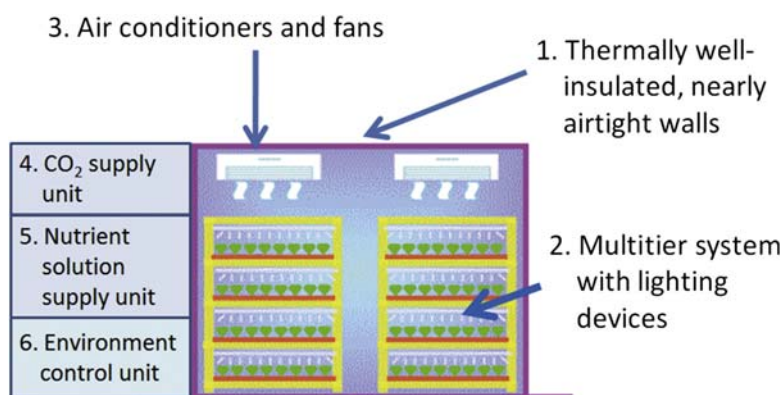


FIGURE 5.1

Configuration of a plant factory as a closed plant production system (CPPS) consisting of six principal components. Electricity is needed for operating Nos. 2 to 6.

Among the resources, a considerable amount of electrical energy is consumed in a PFAL, mainly for lighting and air conditioning. Thus, electrical energy and light energy are the two most important resources for improving the use efficiencies in a PFAL.

5.3 Definition of resource use efficiency

The concept of resource use efficiency (RUE) is schematically shown in Fig. 5.2. With respect to essential resources for growing plants in a PFAL, namely, water, CO₂, light energy, electrical energy, and inorganic fertilizer, the use efficiencies per unit time interval (“hour” is used for unit time in this chapter) are defined as in Eqs. (5.1)–(5.10) and are illustrated schematically in Fig. 5.3 (Li et al., 2012a,b; Ohyama et al., 2000; Yokoi et al., 2003, 2005; Yoshinaga et al., 2000). These are water use efficiency (WUE), CO₂ use efficiency (CUE), light energy use efficiency with respect to PAR_L (LUE_L), light energy use efficiency with respect to PAR_P (LUE_P), electrical energy use efficiency (EUE_L), and inorganic fertilizer use efficiency (FUE_I). PAR_L and PAR_P are photosynthetically active radiation emitted from lamps and received at the plant community surface, respectively. The unit for all variables on the right-hand side of Eqs. (5.1) and (5.3) is kg m⁻² (floor area) h⁻¹. These use efficiencies are defined with respect to the PFAL containing plants. It should be noted that in the fields of plant ecology and agronomy, WUE is defined with respect to plants or plant community (Salisbury and Ross, 1991). CUE in Eq. (5.3) is defined only when CO₂ is supplied or enriched in the PFAL. Methods for estimating the values of variables given on the right-hand side of Eqs. (6.1)–(5.7) are described in Li et al. (2012a,b,c).

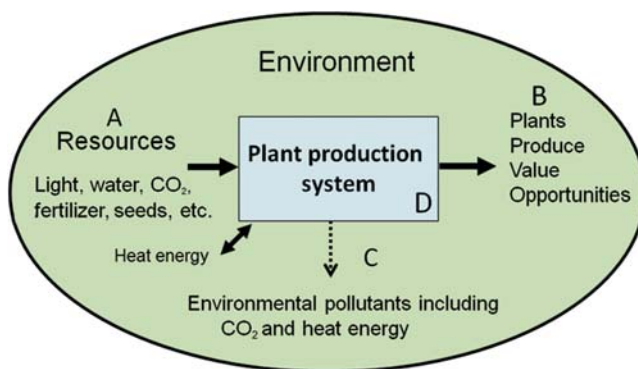


FIGURE 5.2

Scheme showing the concept of resource use efficiency (RUE) of the plant production system. RUE is defined as the ratio of B to A where $A = B + C + D$. RUE is estimated for each resource component. The plant production system is called a “closed plant production system” (CPPS) when each of the resources is converted into produce at its maximum level, so that the resource consumption and emission of environmental pollutants are minimized, resulting in the maximum RUE and lowest cost for resources and pollution processing. A PFAL is one type of CPPS.

WUE is 0.93–0.98 in the PFAL (Fig. 5.4, Table 5.1) and 0.02–0.03 in a greenhouse, meaning that WUE of the PFAL is approximately 30–50 (nearly equal to 0.95/0.03–0.98/0.02) times greater than that of a greenhouse (Ohyama et al., 2000; Kozai, 2013a). Namely, the PFAL is a highly water-saving plant production system compared with a greenhouse. It is noted that WUE increases with increasing leaf area index (LAI) and decreasing N (Fig. 5.5). Thus, air-tightness of the CPPS is essential to achieve a high WUE value.

A PFAL with thermally insulated walls and a high level of air-tightness (N is 0.01–0.02 h^{-1}) must be cooled by air conditioning while the lamps are turned on, even during the cold winter nights in order

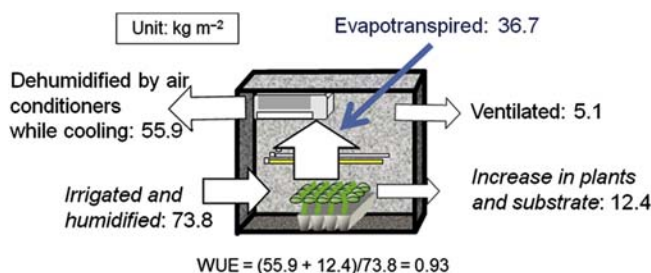


FIGURE 5.4

An experimental result of water use efficiency (WUE) for 14 days in the CPPS. In the case of a greenhouse, the evapotranspired water cannot be reused. Relative humidity was kept at about 80% and air temperature at 30°C (Ohyama et al., 2000).

Table 5.1 Estimated representative values of use efficiencies of water (WUE), CO_2 (CUE), light energy (LUEL), and electrical energy (EUE_L) for a PFAL (plant factory with artificial lighting), and WUE, CUE, and LUEP for a greenhouse with ventilators closed and/or open.

Use efficiency	PFAL	Greenhouse with ventilators closed and enriched CO_2	Greenhouse with ventilators open	Theoretical maximum value for PFAL
WUE (water)	0.95–0.98	N/A	0.02–0.03	1.00
CUE (CO_2)	0.87–0.89	0.4–0.6	See Fig. 5.7	1.00
LUE_L (lamps, PAR_L)	0.027	—	—	About 0.10
LUE_P (plant community)	0.032–0.043 0.05	N/A	0.017 0.003–0.032	About 0.10
EUE_L (electricity)	0.007	—	—	About 0.40

LUE_L and EUE_L are defined only for a PFAL using artificial lamps. N/A (not available) means that the efficiencies of WUE, CUE, and LUE_P can be obtained experimentally but the data were not found in the literature. The maximum value for a PFAL based on a theoretical consideration of each use efficiency is also given in the column “Theoretical maximum value for PFAL.” For the definitions of WUE, CUE, LUE_L , EUE_L , and EUE_P , see Eqs. (5.1)–(5.7) in the text.

The numerical data in this table are cited from or based on the literature: Bugbee and Salisbury (1988), Chiapale et al. (1984), Li et al. (2012a, b, c), Mitchell et al. (2012), Ohyama et al. (2000), Sager et al. (2011), Shibuya and Kozai (2001), Yokoi et al. (2003, 2005), Wheeler (2006), Wheeler et al. (2006).

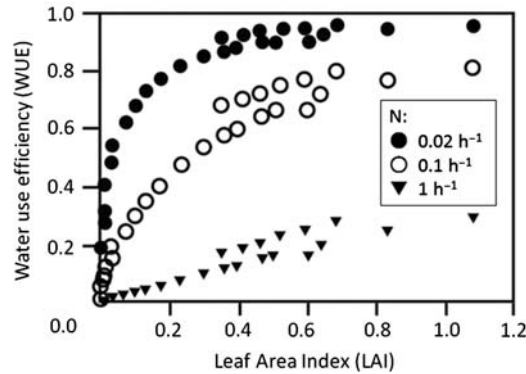


FIGURE 5.5

WUE (water use efficiency) of the CPPS as affected by LAI (leaf area index or ratio of leaf area to cultivation area) and N (number of air exchanges: 0.02, 0.1, and 1 h^{-1}). Water vapor density inside and outside the closed system was assumed to be 16 and 6 g m^{-3} , respectively. All values are simulated values (Yokoi et al., 2005).

to maintain a suitable internal temperature by eliminating the heat generated from the lamps. With cooling, a large portion of the evaporated water, W_C in Eq. (5.1), can be collected as condensation on the cooling panels of the heat pump, and recycled for irrigation. Only a small percentage of W_s is lost to the outside, thanks to the high air-tightness of the PFAL. The N value must be lower than about 0.02 h^{-1} to minimize CO_2 loss to the outside and prevent entry of insects, pathogens, and dust into the culture room.

On the other hand, water vapor evapotranspired in a greenhouse cannot be collected for recycling, because most of it is lost to the outside through ventilation, while the rest of the water vapor mostly condenses on the inner surfaces of the greenhouse walls and so cannot be collected. The amount of water vapor lost to the outside, W_L in Eq. (5.2), increases with increasing $(X_{\text{in}} - X_{\text{out}})$ and N of a greenhouse with ventilators open. N varies in the range of $0.5\text{--}100 \text{ h}^{-1}$ depending on the number of ventilators and degree of opening as well as the wind velocity outside (Chiapale et al., 1984).

If all the lamps are turned off, the relative humidity of the room air in a PFAL approaches 100%, resulting in little transpiration, which may cause physiological disorders of the plants. To avoid this, the tiers in the PFAL are often divided into two or three groups and the lamps in each group are turned on for 12–16 h per day in rotation to generate heat from the lamps at any time of the day so that the heat pumps are running 24 h for dehumidification and cooling of room air.

5.3.2 CO_2 use efficiency

CO_2 use efficiency (CUE) is defined as:

$$\text{CUE} = \frac{C_P}{C_S + C_R} = \frac{C_S - C_L}{C_R + C_S} \quad (5.3)$$

$$C_L = k_c N \frac{V_A (C_{\text{in}} - C_{\text{out}})}{F} \quad (5.4)$$

where C_P is the net photosynthetic rate ($\mu\text{mol m}^{-2} \text{h}^{-1}$); C_S is the CO_2 supply rate ($\mu\text{mol m}^{-2} \text{h}^{-1}$); C_R is the respiration rate of workers in the culture room ($\mu\text{mol m}^{-2} \text{h}^{-1}$), if any; and C_L is the rate of loss of CO_2 to the outside due to air infiltration ($\mu\text{mol m}^{-2} \text{h}^{-1}$). C_R can be estimated using data on the number of workers, working hours per person, and hourly amount of CO_2 released by human respiration per person (about 0.05 kg h^{-1}) (Li et al., 2012b). In Eq. (5.4), N , F , and V_A are the same as in Eq. (5.2), and C_{in} and C_{out} are, respectively, CO_2 concentration inside and outside the culture room ($\mu\text{mol mol}^{-1}$); k_C is the conversion factor from mol to volume ($0.0245 \text{ m}^3 \text{ mol}^{-1}$ at 25°C). It should be noted that CO_2 is often purchased by weight. The conversion factor from volume to mass (weight) is 1.80 kg m^{-3} at 25°C .

It is assumed in Eq. (5.4) that C_{in} at time t is the same as at time $(t + \delta)$ where δ is the estimation time interval. If not, the term $\frac{C_{\text{in}}(t) - C_{\text{in}}(t + \delta)VA}{\delta t}$ is added on the right-hand side of Eq. (5.4), the value of which is negligibly small in most cases. In a case where C_{out} changes with time during the estimation time interval, the average value is used in Eq. (5.4).

CUE is about 0.87–0.89 in a PFAL with N of 0.01 – 0.02 h^{-1} and CO_2 concentration of $1000 \mu\text{mol mol}^{-1}$ (Fig. 5.6, Table 5.1), whereas CUE is around 0.5 in a greenhouse with ventilators closed having N of about 0.1 h^{-1} and enriched CO_2 concentration of $700 \mu\text{mol mol}^{-1}$ (Yoshinaga et al., 2000; Ohshima et al., 2000). Thus, CUE is roughly 1.8 ($= 0.88/0.50$) times higher in a PFAL than in a greenhouse with all ventilators closed and CO_2 enrichment (Yokoi et al., 2005). This is because the amount of CO_2 released to the outside, C_L in Eq. (5.4), increases with increasing N and $(C_{\text{in}} - C_{\text{out}})$ (Fig. 5.6). It is thus natural that the set point of CO_2 concentration for CO_2 enrichment is generally higher (1000 – $2000 \mu\text{mol mol}^{-1}$) in a PFAL than in a greenhouse (700 – $1000 \mu\text{mol mol}^{-1}$).

When N and $(C_{\text{in}} - C_{\text{out}})$ of the PFAL are constant with time, CUE increases with increasing LAI (leaf area index or ratio of leaf area to cultivation area) in the range of 0 – 3 (Yoshinaga et al., 2000). This is because, in Eq. (5.3), C_P increases with increasing LAI but C_L is not affected by LAI. CUE also increases with increasing net photosynthetic rate per unit planting area (Fig. 5.7). In order to maintain a high CUE regardless of LAI, the set point of the CO_2 concentration for CO_2 enrichment should be increased with increasing LAI and/or the net photosynthetic rate.

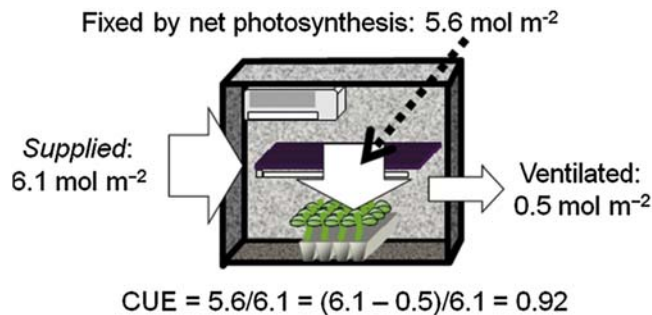


FIGURE 5.6

An experimental result of CUE (CO_2 use efficiency) during 15 days in the CPPS at $N = 0.01 \text{ h}^{-1}$. CO_2 concentration during the photoperiod was kept at about 1000 ppm (Yoshinaga et al., 2000). One mole of CO_2 is equal to 44 g .

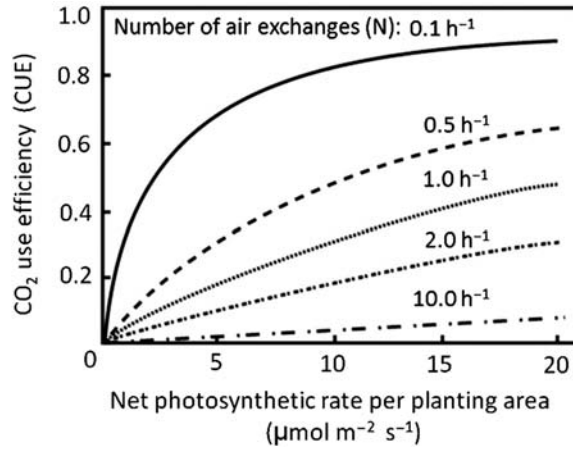


FIGURE 5.7

CUE (CO₂ use efficiency) as affected by net photosynthetic rate and N (number of air exchanges). Assumptions for calculation: floor area: 1000 m², room air volume: 3000 m³; N : 0.1, 0.5, 2.0, and 10 h⁻¹; CO₂ conc. inside and outside: 1000 and 350 μmol mol⁻¹; air temperature inside and outside: 27 °C; planting area is covered with plants; soil respiration is negligibly small (Yoshinaga et al., 2000). N is 10–100 h⁻¹ when roof and/or side ventilators are open.

5.3.3 Light energy use efficiency of lamps and plant community

The light energy use efficiencies of lamps and plant community (LUE_L and LUE_P) are defined as:

$$\text{LUE}_L = \frac{fD}{\text{PAR}_L} \quad (5.5)$$

$$\text{LUE}_P = \frac{fD}{\text{PAR}_P} \quad (5.6)$$

where f is the conversion factor from dry mass to chemical energy fixed in dry mass (about 20 MJ kg⁻¹); D is the dry mass increase rate of whole plants or salable parts of the plants in the PFAL (kg m⁻² h⁻¹); and PAR_L and PAR_P are, respectively, photosynthetically active radiation (PAR) emitted from the lamps and received at the plant community surface in the PFAL (MJ m⁻² h⁻¹).

LUE_L and LUE_P can also be defined, respectively, as $b \times C_p / \text{PAR}_L$ and $b \times C_p / \text{PAR}_P$ where b is the minimum PAR energy to fix 1 mole of CO₂ in plants (0.475 MJ mol⁻¹) and C_p is the net photosynthetic rate of plants (μmol m⁻² h⁻¹). The ratio of PAR_P to PAR_L is often referred to as the “utilization factor” in illumination engineering.

The average LUE_P for tomato seedling production in a greenhouse was 0.017 (Shibuya and Kozai, 2001). On the other hand, the average LUE_L for tomato seedling production in a PFAL was 0.027 (Yokoi et al., 2003). It should be noted, however, that LUE_L of the PFAL in Eq. (5.5) is estimated based on PAR_L emitted from the lamps (Takatsuji and Mori, 2011; Yokoi et al., 2003), whereas LUE_P in Eq. (5.6) of a greenhouse is estimated based on PAR_P received at the community surface. The ratio PAR_P/PAR_L is estimated to be 0.63–0.71 (Yokoi et al., 2003). Thus, LUE_P in the PFAL would be

approximately in the range between 0.038 (= 0.027/0.71) and 0.043 (= 0.027/0.63), which is 1.9 (= 0.032/0.017) to 2.5 (= 0.043/0.017) times higher than that in a greenhouse.

The maximum LUE_P , which is closely related to the inverse of “quantum yield,” is estimated to be in the order of 0.1 (Salisbury and Ross, 1991; Bugbee and Salisbury, 1988). The LUE_P of various crops in space research by NASA in the US is around 0.05 (Massa et al., 2008; Sager et al., 2011; Wheeler, 2006; Wheeler et al., 2006). It should be noted that the LUE_P and LUE_L values shown in Fig. 5.8 are significantly higher than those found by NASA; further careful experiments are necessary to verify the accuracy of measurements. Regardless, there should be room to improve the LUE_L and LUE_P of the PFAL. Approaches to doing so will be described later in this chapter.

5.3.4 Electrical energy use efficiency of lighting

The electrical energy use efficiency of lighting (EUE_L) is defined as:

$$EUE_L = hLUE_L = \frac{f h D}{PAR_L} \quad (5.7)$$

where h is the conversion coefficient from electrical energy to PAR_L energy, which is around 0.25 for white fluorescent lamps, and 0.3–0.4 for recently developed LEDs (Mitchell et al., 2012; Takatsuji and Mori, 2011). The electrical energy consumed by lamps, A_L , can be expressed as:

$$A_L = \frac{PAR_L}{h} \quad (5.8)$$

EUE_L , LUE_L , and LUE_P in a PFAL increase almost linearly with increasing LAI at LAI of 0–2.5 (Yokoi et al., 2003) (Fig. 5.8).

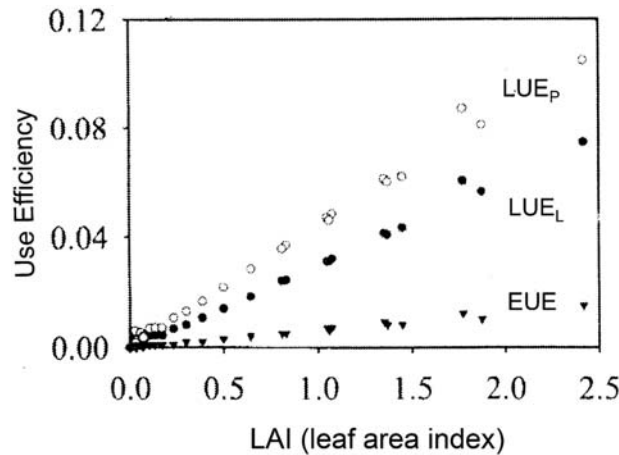


FIGURE 5.8

LUE_P (LUE with respect to PAR at the plant community level), LUE_L (LUE with respect to PAR emitted from fluorescent lamps), and EUE (electric energy use efficiency) as affected by LAI (leaf area index) (Yokoi et al., 2003). PAR : photosynthetically active radiation. By using LEDs, the LUE_L would be improved by 30%–40%.

5.3.5 Electrical energy use efficiency of heat pumps for cooling

The electrical energy use efficiency of heat pumps for cooling (COP) is defined as:

$$\text{COP} = \frac{H_h}{A_A} \quad (5.9)$$

where H_h is the heat energy removed from the culture room by heat pumps (air conditioners) ($\text{MJ m}^{-2} \text{h}^{-1}$) and A_A is the electricity consumption of the heat pumps ($\text{MJ m}^{-2} \text{h}^{-1}$). This efficiency is often referred to as the coefficient of performance (COP) for cooling of heat pumps; more information regarding COP is described later in this chapter.

5.3.6 Inorganic fertilizer use efficiency

Inorganic fertilizer use efficiency (FUE_I) is defined as:

$$\text{FUE}_I = \frac{I_U}{I_S} \quad (5.10)$$

where I_U is the absorption rate of ion element I of inorganic fertilizer by plants, and I_S is the supply rate of I to the PFAL. I includes nitrogen (NO_3^- , NO_4^+), phosphorus (PO_4^-), potassium (K^+), etc. N is dissolved in water as NH_4^+ or NO_3^- , but is counted as N in Eq. (5.10). Thus, N use efficiency, P use efficiency, K use efficiency, and so forth, can be defined for each nutrient element.

Culture beds in the PFAL are isolated from soil, and the nutrient solution drained from the culture beds is returned to the nutrient solution tank for recirculation. Nutrient solution is rarely discharged to the outside, usually about once or twice a year when certain ions such as Na^+ and Cl^- , which are not well absorbed by plants, have excessively accumulated in the nutrient solution or when the culture beds have become accidentally contaminated by certain pathogens. In these cases, the supply of fertilizer is stopped for several days before removing the plants from the culture beds so that most nutrient elements in the culture beds and nutrient tank are absorbed by the plants. As a result, the water discharged from the PFAL to the outside is relatively clean. Therefore, FUE_I of the PFAL should be fairly high, although no literature regarding this subject could be found.

On the other hand, FUE_I of a greenhouse and an open field is relatively low, which occasionally causes salt accumulation on the soil surface (Nishio, 2005). In an open field, excess supply of nitrates and phosphates occasionally causes nutrient run-off and leaching, resulting in eutrophication of rivers and lakes (Nishio, 2005; Sharpley et al., 2003).

5.4 Representative values of resource use efficiency

WUE, CUE, LUE, and EUE for a PFAL found in the literature are summarized in Table 5.1 and compared with those of a greenhouse with ventilators closed and/or open, together with their theoretical maximum values. In the table, LUE_L and EUE_L are defined only for a PFAL using lamps; N/A (not available) means that the efficiencies of WUE and LUE_P can be obtained experimentally but data were not found in the literature.

The table shows that WUE and CUE of the PFAL are considerably higher than those of a greenhouse with ventilators open. LUE_P of PFAL ranges from 0.032 to 0.043, while LUE_P of a greenhouse with ventilators open varies from 0.003 to 0.032. As for PFAL, LUE_L of 0.027 is 63%–84% of LUE_P of 0.032–0.043, which means that PAR_P was 63%–84% of PAR_L .

LUE_L and EUE_L in Table 5.1 are, respectively, 0.027 and 0.007, which means that 2.7% of PAR energy and 0.7% of electrical energy were converted into chemical energy contained in dry matter of plants. The chemical energy contained in dry matter is 20.0 MJ kg^{-1} (Eqs. 5.5 and 5.6). Thus, the electricity required to produce 1 kg of dry matter is 2857 ($= 20.0/0.007$) MJ/kg or 794 ($= 2857/3.6$) kWh. Similarly, the PAR energy required to produce 1 kg of dry matter is 740 ($= 20.0/0.027$) MJ/kg or 205 ($= 740/3.6$) kWh.

The WUE and CUE in a PFAL for tomato seedling production were determined by Yokoi et al. (2005). WUE and CUE increased as LAI increased and the number of air exchanges decreased. The maximum WUE (0.95–0.98) and CUE (0.87–0.89) were obtained at the maximum LAI of 1.2 and minimum number of air exchanges of 0.02 h^{-1} .

5.5 Electricity consumption and cost

Commercial production from a PFAL is limited to value-added plants because the electricity consumption for lighting to increase the dry mass of plants is significant: the electricity cost typically accounts for 25% of the total production cost (Kozai, 2012). Accordingly, the plants that are suitable for production in a PFAL are those that can be grown at a high planting density (50–1000 plants/ m^2) to a harvestable stage in a short cultivation period (30–60 days) under relatively low light intensity ($100\text{--}300 \mu\text{mol m}^{-2} \text{ s}^{-1}$). Also, mature plants need to be shorter than around 30 cm because the multitier system must be used to increase annual productivity per unit floor area.

The electricity consumption in the culture room of a PFAL per unit floor area ($\text{MJ m}^{-2} \text{ h}^{-1}$), A_T , and its components are given by:

$$A_T = A_L + A_A + A_M \quad (5.11)$$

$$A_A = \frac{A_L + A_M + H_V}{\text{COP}} = \frac{H_h}{\text{COP}} \quad (5.12)$$

where A_L , which is expressed as PAR_L/h in Eq. (5.8), is the electricity consumption for lighting; A_A is that for air conditioning; and A_M is that for other equipment such as air circulation fans and nutrient solution pumps. H_V is the cooling load due to air infiltration and heat penetration through the walls, both of which account for only a small percentage of A_A . H_h is the heat energy removed from the PFAL using heat pumps. COP is the coefficient of performance of heat pumps as defined by Eq. (5.9), which increases with decreasing outside temperature at a given room air temperature.

On the annual average, A_L , A_A , and A_M of a PFAL account for, respectively, 80%, 16%, and 4% of A_T in Tokyo (Ohyama et al., 2002b) (Table 5.2). The annual average COP for cooling in a PFAL with room air temperature of 25°C was 5–6 in Tokyo where the annual average temperature is about 15°C ; COP was approximately 4 in summer and 10 in winter (Ohyama et al., 2002a) (Fig. 5.9). Thus, in order to reduce the total electricity consumption, it is most efficient to reduce A_L by improving LUE_L , followed by improving COP.

Table 5.2 Percentages of annual electricity consumption by components (Ohyama et al., 2002b). The percentages remain the same for LEDs, with reduced electricity consumption.

Purpose	Percentage	Equipment
Lighting	80%	Fluorescent lamps 40 W
Cooling	16%	Heat pumps (air conditioners)
Others	4%	Water pumps, fans, etc.

The COP of the heat pump is estimated to be ca. 5.25 ($= (80 + 4)/16 = 5.25$).

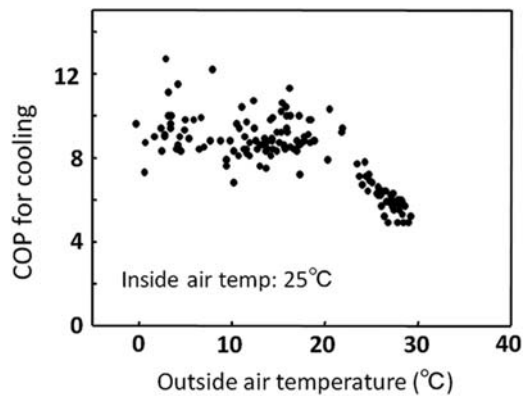


FIGURE 5.9

COP for cooling of room air conditioner (or heat pump) as affected by outside air temperature (Ohyama et al., 2002a).

5.6 Improving light energy use efficiency

5.6.1 Introduction

There are various methods to improve LUE_L in Eq. (5.5) and thus EUE_P in Eq. (5.6) (Kozai, 2011). However, as there has been little research on improving LUE_L , some of the methods described in the following paragraphs are not based on experimental data, but rather on a theoretical consideration and practical experience in commercial plant production using PFALs.

Fig. 5.10 shows the process of converting electrical energy into chemical energy for the salable portion of plants with current representative values. At present, less than 1% of electrical energy is converted into the salable portion of plants; the remaining ca. 99% is converted into heat energy, which is removed to the outside by air conditioners. The research described in the following paragraphs shows that this conversion factor can be improved to 3% or higher (Fig. 5.11).

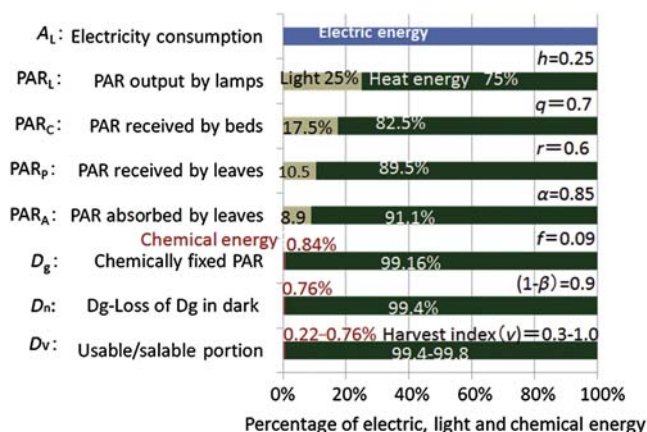


FIGURE 5.10

Process of converting electrical energy for lighting in the PFAL with FL lamps into chemical energy contained in the salable portion of plants.

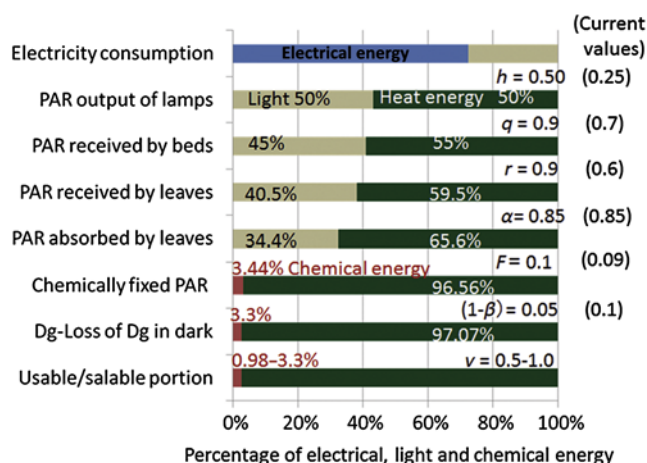


FIGURE 5.11

Maximum possible and existing processes of converting electrical energy for lighting in the PFAL into chemical energy contained in the salable portion of plants.

5.6.2 Interplant lighting and upward lighting

Traditional overhead lighting provides an uneven light distribution and causes mutual shading in a dense canopy and senescence of lower leaves. Interplant or intracanopy lighting can provide more light to the lower leaves, improve the light distribution, and thus enhance photosynthesis of the whole canopy. This is because the net photosynthetic rate of the lower leaves, which is often negative or nearly zero, will be made positive by interplant lighting (Dueck et al., 2006).

The benefits of interplant lighting have already been reported in greenhouse plant production and under controlled environments. Adding additional light within a cowpea canopy significantly delayed senescence of the interior leaves in the canopy (Frantz et al., 2000). Greenhouse cucumber yields were increased through intracanopy supplemental lighting in Canada and Europe (Hao et al., 2012; Petersen et al., 2010). LEDs are a feasible light source for interplant lighting because of their small volume and lower surface temperature compared to other light sources.

5.6.3 Improving the ratio of light energy received by leaves

The LUE_L increases with increasing ratio of the light energy received by leaves to the light energy emitted by lamps. This ratio can be improved by well-designed light reflectors, reduction in vertical distance between lamps and plants, increase in distance between plants (or planting density) as plants grow, and other such measures (Massa et al., 2008). The ratio increases linearly from zero up to unity with increasing LAI from 0 to 3 (Yokoi et al., 2003). Thus, LUE_L can be significantly improved by maintaining LAI at around 3 throughout the culture period by automatic or manual spacing of plants.

5.6.4 Using LEDs

A direct method of improving EUE_L is to use a light source with a high h value in Eq. (5.7). The h value for recently developed LEDs is around 0.4 (Liu et al., 2012), whereas that of fluorescent lamps (FL) is around 0.25 (Kozai, 2011). Although the price of LEDs with h of about 0.4 is several times higher than that of FL as of 2013, the price has decreased considerably every year and this trend will continue. The spectral distribution or light quality of LED lamps affects plant growth and development and consequently LUE_L (Jokinen et al., 2012; Liu et al., 2012; Massa et al., 2008; Mitchell et al., 2012; Morrow, 2008). Refer to Kozai et al. (2016) and Kozai (2018) for recent advances in LED lighting.

5.6.5 Controlling environmental factors other than light

LUE_L is largely affected by the plant environment and ecophysiological status of plants, as well as by the genetic characteristics of plants. An optimal combination of temperature, CO_2 concentration, air current speed, water vapor pressure deficit, and the composition, pH, and electrical conductivity (EC) of the nutrient solution must be found in order to improve LUE_L for each crop (Bugbee and Salisbury, 1988; Evans and Poorter, 2001; Dueck et al., 2006; Kozai, 2011; Liu et al., 2012; Morrow, 2008; Nederhoff and Vegter, 1994; Sager et al., 2011; Thongbai et al., 2011; Wheeler, 2006; Wheeler et al., 2006; Yabuki, 2004).

The optimal light level for plant growth and development varies with species and growth stage. For example, high light intensity and high CO_2 concentration may have a limited effect on increasing biomass when plants are too small. Similarly, no further increase in light intensity is needed when the plant response to light reaches a plateau. Therefore, it is important to find the most economic minimum light levels in a PFAL for crops in order to increase LUE_L .

5.6.6 Controlling air current speed

A horizontal air current speed of $0.3\text{--}0.5\text{ m s}^{-1}$ within the plant community enhances the diffusion of CO_2 and water vapor from room air into the stomatal cavity in leaves, and consequently photosynthesis, transpiration, and plant growth, if the vapor pressure deficit (VPD) is controlled at an optimum level (Yabuki, 2004; Kitaya, 2018). The control of air current speed in accordance with plant growth stage by changing the rotation speed of fans is an advantage of the PFAL for improving plant growth. Yokoi et al. (2007) showed that the growth and uniformity of tomato seedlings in a CPPS are enhanced at a higher air current speed (0.7 m s^{-1}) than at a lower speed (0.3 m s^{-1}). They also reported suppression of growth and less uniformity at higher planting density at higher air current speed than at low air current speed.

5.6.7 Increasing the salable portion of plants

Electricity is consumed to produce whole plants consisting of leaves with petioles, roots, stems, and sometimes flower stalks and buds. Thus, in order to improve EUE_L and LUE_L of the salable parts of plants, it is important to minimize the dry mass of the nonsalable portion. Leaf vegetables such as lettuce plants should be grown with a minimum percentage of root mass, typically less than 10% of the total mass. This is not so difficult because water stress of plants can be minimized by controlling VPD of the room air and water potential of the nutrient solution in the culture beds of a PFAL. In the case of root crops such as turnip plants, the salable portion can be significantly increased by harvesting them earlier than usual so that the aerial part will be edible. This is often practiced in commercial PFALs (Fig. 5.12).

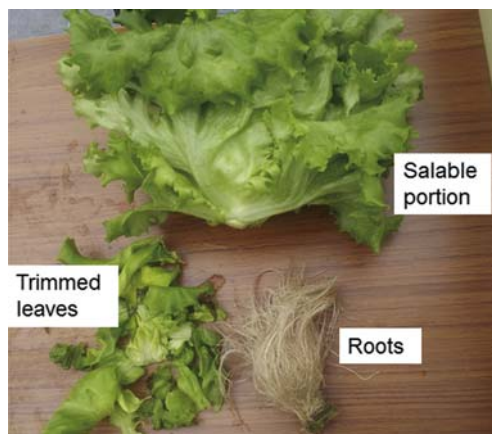


FIGURE 5.12

Salable and unsalable portions (roots and trimmed leaves) of lettuce plants grown in the PFAL. Trimmed leaves are yellowed, small outer leaves, and/or damaged. Fresh weight of roots and trimmed leaves account for less than 10% and ca. 5% of total fresh weight, respectively.

5.6.8 Increasing annual production capacity and sales volume per unit land area

The relative annual production capacity per unit land area of an existing PFAL with 10 tiers is more than 100 and 150 times, respectively, that of an open field and can be 200 and 250 times, respectively, by improving the following factors: (1) shortening the culture period from transplanting to harvest through optimal environmental control; (2) increasing the ratio of cultivation area of each tier to floor area; and (3) increasing percentages of salable plants and salable portion of plants. The relative annual sales price of PFAL-grown lettuce is generally 1.2–1.5 times that of field-grown plants due to improved quality, resulting in an increase in relative annual sales volume.

5.7 Estimation of rates of photosynthesis, transpiration, and water and nutrient uptake

5.7.1 Introduction

Interactions between plants and their environments in a PFAL equipped with a hydroponic culture system are fairly simple compared with those in a greenhouse and open field. This is because the PFAL is thermally well-insulated and nearly airtight, so the environment is not affected by the weather, especially the fluctuations in solar radiation with time. Therefore, the energy and mass balance of the PFAL and related rate variables (namely, flows that include the time dimension in units) such as those given in Eqs. (5.1) and (5.2) can be measured, evaluated, and controlled relatively easily (Li et al., 2012a,b,c).

The quality of environmental control will be significantly improved by monitoring, visualizing, understanding, and controlling the RUE (WUE, CUE, LUE_L, EUE_L, and FUE) in Eqs. (5.1)–(5.10) and rate variables. The rate variables include the rates of net photosynthesis (gross photosynthesis minus dark and photorespirations), dark respiration, transpiration, water uptake, and nutrient uptake, which represent the ecophysiological status of the plant community. Another group of rate variables includes the supply rates of CO₂, irrigation water, fertilizer constituents, and electricity consumption by its components in the PFAL.

The set points of environmental factors can be determined, for example, for maximizing LUE_L, with the minimum resource consumption or at the lowest cost (Kozai, 2011). In order to maximize the cost performance (ratio of economic benefit to production cost) instead of maximizing LUE_L, the concept and method of integrative environmental control must be introduced (Dayan et al., 2004; Kozai et al., 2011). Continuous monitoring, visualization, and control of the rate variables and RUE will become important research subjects in integrated environmental control for plant production using the PFAL (Dayan et al., 2004; Kozai et al., 2011).

5.7.2 Net photosynthetic rate

The net photosynthetic rate (C_p) at time t during the time interval of δt can be estimated by modifying Eqs. (5.3) and (5.4) as follows:

$$C_p = C_s + C_r - \left(k_c N \frac{V_A}{F} \right) (C_{in} - C_{out}) + \frac{\left(\frac{k_c V_A}{F} \right) \left(C_{in} \left(t + \frac{\delta t}{2} \right) - C_{in} \left(t - \frac{\delta t}{2} \right) \right)}{\delta t} \quad (5.13)$$

where the fourth term expresses the change in CO₂ mass in the air of the culture room during the time interval of δt between $t - \frac{\delta t}{2}$ and $t + \frac{\delta t}{2}$. In practical applications, δt would be 0.5–1.0 h. C_p can be estimated fairly accurately using Eq. (5.13), since (1) k_c and V_A are constant; (2) C_S , C_{in} , and C_{out} can be accurately measured; and (3) N can be estimated using Eq. (5.13) as described later. Dark respiration rate can be estimated using the same Eq. (5.13) during the dark period. Under steady-state conditions, Eq. (5.13) is simplified and estimation of C_p and CUE is easy (Fig. 5.13).

5.7.3 Transpiration rate

In a PFAL, the transpiration rate of plants grown in the hydroponic culture beds in the PFAL at time t during the time interval of δt , W_T , can be estimated by:

$$W_T = W_C + \left(N \frac{V_A}{F} \right) (X_{in} - X_{out}) + \frac{\left(\frac{V_A}{F} \right) \left(X_{in} \left(t + \frac{\delta t}{2} \right) - X_{in} \left(t - \frac{\delta t}{2} \right) \right)}{\delta t} \quad (5.14)$$

where the third term expresses the change in water vapor mass in the air of the culture room during the time interval of δt between $t - \frac{\delta t}{2}$ and $t + \frac{\delta t}{2}$. Since V_A and F are constants, and W_C , X_{in} , and X_{out} can be measured relatively accurately, N can be estimated for the time interval of $t - \frac{\delta t}{2}$ and $t + \frac{\delta t}{2}$ using Eq. (5.14) (Dayan et al., 2004; Kozai et al., 2011; Li et al., 2012a):

$$N = \frac{W_T - W_C - \frac{\left(\frac{V_A}{F} \right) \left(X_{in} \left(t + \frac{\delta t}{2} \right) - X_{in} \left(t - \frac{\delta t}{2} \right) \right)}{\delta t}}{\left(\frac{V_A}{F} \right) (X_{in} - X_{out})} \quad (5.14)$$

In the PFAL, no evaporation from the substrate in the culture can be assumed, because the culture beds are covered with plastic panels with small holes for growing plants. Furthermore, neither evaporation nor condensation from/to the walls and floor can be assumed, because the walls and floor are thermally well-insulated.

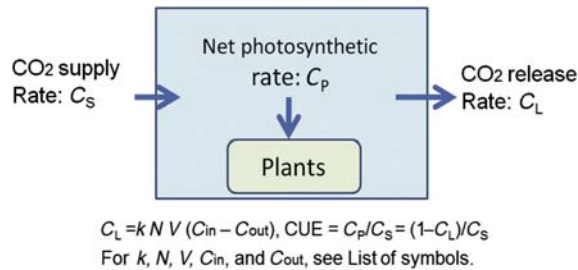


FIGURE 5.13

Scheme showing the method for estimating hourly net photosynthetic rate (C_S) and CUE based on the CO₂ balance of the PFAL under steady-state conditions. For unsteady conditions, see Eq. (5.13). The set point of C_{in} is determined by considering CUE, costs for C_S and C_L , and benefit by C_p .

5.7.4 Water uptake rate by plants

Water uptake rate (W_U) can be expressed by modifying Eq. (5.14) as:

$$W_U = W_P + W_t \quad (5.15)$$

where W_P is the change in water mass of plants during time interval δt which is difficult to estimate accurately. On the other hand, W_U can be estimated relatively easily by the equation:

$$W_U = W_{in} - W_{out} - \frac{\left(\frac{k_{LW}}{F}\right) \left(V_{LW} \left(t + \frac{\delta t}{2}\right) - V_{LW} \left(t - \frac{\delta t}{2}\right)\right)}{\delta t} \quad (5.16)$$

where W_{in} and W_{out} are, respectively, the flow rate of nutrient solution into and from the culture beds. k_{LW} is a conversion factor from volume to mass of liquid water (997 kg m⁻³ at 25°C and 101.3 kPa). $V_{LW} \left(t + \frac{\delta t}{2}\right) - V_{LW} \left(t - \frac{\delta t}{2}\right)$ is the change in nutrient solution volume in the culture beds and/or the nutrient solution tank during the time interval of δt . W_U in Eq. (5.16) can be estimated for each culture bed or for all the culture beds by changing the measuring points of W_{in} and W_{out} .

5.7.5 Ion uptake rate by plants

The ion uptake rate by plants in the culture bed, I_U , can be estimated by:

$$I_U = I_{in} W_{in} - I_{out} W_{out} + \frac{\left(\frac{I_{in} + I_{out}}{2}\right) \left(V_{LW} \left(t + \frac{\delta t}{2}\right) - V_{LW} \left(t - \frac{\delta t}{2}\right)\right)}{\delta t} \quad (5.17)$$

where I_{in} and I_{out} are, respectively, the concentration of ion I at the inlet and outlet of the culture bed. W_{in} and W_{out} are, respectively, the flow rate of nutrient solution at the inlet and outlet of the culture bed. The third term shows the change in amount of ion I in the culture bed during the time interval of δt . I_U can be measured for each culture bed, more than one culture bed, or all the culture beds.

5.7.6 Application

The methods of estimating rate variables given previously can be applied to small PFAL-type plant growth chambers used for research, education, self-learning, and hobby purposes (Kozai, 2013b), as well as PFALs for commercial plant production. Since all the major rates and state variables in the PFAL can be measured and graphically displayed, the quantitative relationships among these variables can be analyzed and understood relatively easily. This benefit could be increased by displaying the relationships together with camera images of the plants. Major rates and state variables of the PFAL are schematically shown in Fig. 5.3.

5.8 Coefficient of performance of heat pump

A heat pump is a device that provides heat energy from a source of heat to a destination called a “heat sink.” Heat pumps are designed to move heat energy in the direction opposite to that of spontaneous

heat flow by absorbing heat from a cold space and releasing it to a warmer one, and vice versa. A heat pump uses external power to accomplish the work of transferring energy from the heat source to the heat sink. Electrically driven heat pumps are commonly used for heating, ventilation, and air conditioning.

The term *coefficient of performance* (COP), as defined by Eq. (5.9), is the ratio of heating or cooling provided to electrical energy consumed. Higher COPs equate to lower operating costs. COP is highly dependent on operating conditions, especially the difference in temperature between the inner and outer units (or the evaporator and condenser) of the heat pump and the ratio of actual cooling/heating load. The COPs for heating and cooling are different because the heat reservoir of interest is different. For cooling, the COP is the ratio of the heat removed from the cold reservoir to the input work. However, for heating, the COP is the ratio of the heat removed from the cold reservoir plus the heat added to the hot reservoir to the input work.

In a plant factory under artificial light, heat pumps are principally working in the cooling mode even in the winter months in cold regions due to the heat produced by lights. To prevent high humidity, the lights are turned on alternately at different tiers in the PFAL so that some lights always remain on to keep the heat pumps running. In this case, the COP for cooling ranges from 8 to 12 with an inside air temperature of 25°C and outside temperatures ranging from 0 to 15°C (Kozai, 2012). The electricity consumption for cooling is usually 1/10th to 1/15th that of lighting because 80% of the cooling load is required to remove the heat produced by the lights.

Thanks to technological progress, COP values have improved considerably in recent years. For example, at an outside temperature of 34°C and an inside temperature of 27°C, the COP of household heat pumps (air conditioners) for cooling was improved from 2.5–3.0 in 1994 to 5–6 in 2009, doubling the efficiency in 15 years (Kozai, 2012). Research has shown the potential of using heat pumps for controlling the environment in greenhouses. Tong et al. (2010) reported an average hourly COP of 4.0 when heat pumps were used for heating a greenhouse to maintain the inside temperature at 16°C with outside temperatures ranging from –5 to 6°C. In the heating mode, COP decreases as the outside temperature decreases. For cooling a greenhouse to maintain the inside temperature at 18°C with outside air temperatures ranging from 21 to 28°C, the average hourly COP was 9.3 (Tong et al., 2013). Similarly, in the cooling mode, COP decreases as outside temperature increases.

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Micro- and mini-PFALs for improving the quality of life in urban areas

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6.1 Introduction

The global urban population was 4.2 billion people (55%) in 2018 and is expected to exceed 5 billion by 2030. At the same time, the population living in agricultural areas is predicted to decrease to 3 billion due to the increasing percentage of aged farmers and growers. Consequently, the traditional system of producing almost all food including fresh produce in agricultural areas and transporting it to urban areas will have to be changed in the coming decades (Despommier, 2010; United Nations, 2017).

To enhance local production of fresh, clean vegetables for local consumption, urban agriculture, especially PFALs (plant factories with artificial lighting), has become increasingly important in Japan and other countries with densely populated urban areas, as described in Chapters 2 and 3.

In parallel with the commercial production of leafy vegetables using PFALs, urban residents with little opportunity to grow plants outdoors have started enjoying indoor farming using a household PFAL or micro-PFAL in Japan, Taiwan, China, and several other Asian countries and regions (Takagaki et al., 2014).

In addition, mini-PFALs have recently been set up for various purposes at restaurants, cafés, shopping centers, schools, community centers, hospitals, etc. Such micro- and mini-PFALs are referred to as “m-PFALs” in this chapter. It is suggested here that m-PFALs and their networks have the potential to help create a new lifestyle for people living in urban areas.

6.2 Characteristics and types of m-PFALs

m-PFALs are closed or semiclosed indoor plant-growing systems used for various purposes other than commercial plant production and sales. m-PFALs are characterized by: (1) hydroponic or soilless culture; (2) plants grown mostly under LED lamps; (3) well-designed as furniture or a green interior (attractive, safe, and robust); (4) easy to use and maintain; (5) no use of pesticides; and (6) lighting period, watering, temperature, etc. can be controlled automatically or manually depending on the

user's choice. Most micro-PFALs range in size (air volume of plant-growing space) from 0.03 m^3 (e.g., $0.2 \times 0.5 \times 0.3 \text{ m}$) and 1 m^3 (e.g., $1.0 \times 0.5 \times 2 \text{ m}$) and most mini-PFALs range from 2 m^3 (e.g., $2 \times 0.5 \times 2 \text{ m}$) to 30 m^3 (e.g., $2 \times 5 \times 3 \text{ m}$).

m-PFALs are divided into three types: Type A is not air-conditioned but instead uses natural or forced ventilation through air gaps covered with fine mesh nets to prevent the entry of insects; Type B is air-conditioned by either an air-cooled or water-cooled system and also uses some degree of natural ventilation, but has no CO_2 enrichment system; and Type C is an airtight structure equipped with an air conditioner and CO_2 enrichment unit. Types A and B produce vegetables and/or herbs that can be eaten fresh after washing with tap water. Type C produces vegetables that can be eaten fresh without washing because they are kept highly clean. Most m-PFALs are Type A or Type B, while most PFALs for commercial plant production are Type C.

In Types B and C, the air conditioner is used for cooling to remove the heat generated by the lamps. The water vapor transpired from the leaves is condensed into liquid water at the cooling panels of the air conditioner, and the condensed water is returned to the nutrient solution tank for recycling. Thus, the amount of fresh water to be added by the user to the nutrient solution tank is minimized, and a drainage pipe system is not required.

6.3 m-PFALs in various scenes

6.3.1 Homes

m-PFALs are used at home by an individual or family (Figs. 6.1A and B). Using the m-PFAL instead of an outdoor farm, beginners can relatively easily grow a variety of leafy vegetables, herbs, small root vegetables, and edible flowers all year round. The user can choose the support mode to indicate how much assistance by m-PFAL software is necessary to grow plants. These m-PFALs help create a green interior that benefits people's well-being by caring for the plants and watching them grow, and the plants serve as fresh produce.



FIGURE 6.1A

Tabletop m-PFAL for personal use (The Plant Environment Designing Program by H. Hara).



FIGURE 6.1B

m-PFALs as green furniture purchasable on the Internet. Estimated retail prices of (A), (B), and (C) are about 1500, 200, and 100 US\$. Products of U-ING Co., Ltd (<http://www.greenfarm.uing.u-tc.co.jp/tri-tower>).

It is enjoyable to grow and harvest plants outdoors under favorable weather conditions. However, some people live in regions that are too cold or hot for outdoor farming, while others only have spare time at night. With the m-PFAL, people can enjoy growing plants indoors at any time, even on cold, windy, rainy nights or on hot and humid days.

The monthly electric energy consumption of a micro-PFAL that produces enough leafy vegetables for fresh salads for two adults is about 50 kWh ($= 0.1 \text{ kW} \times 16 \text{ h/d} \times 30 \text{ d/month}$), and the monthly electricity charge is about 5 US\$ in the United States or about 10 US\$ in Japan.

6.3.2 Restaurants and shopping centers

m-PFALs are placed at the entrances of restaurants, cafés, and shopping centers to catch people's attention (Figs. 6.2A, 6.3, 6.4). Vegetables, herbs, and medicinal plants are grown at the restaurants and served to customers. The chef picks the plants 5 minutes before serving them, and the customers can see how the vegetables are grown in the m-PFAL. Café Agora has created a sustainable business model (Fig. 6.2B).

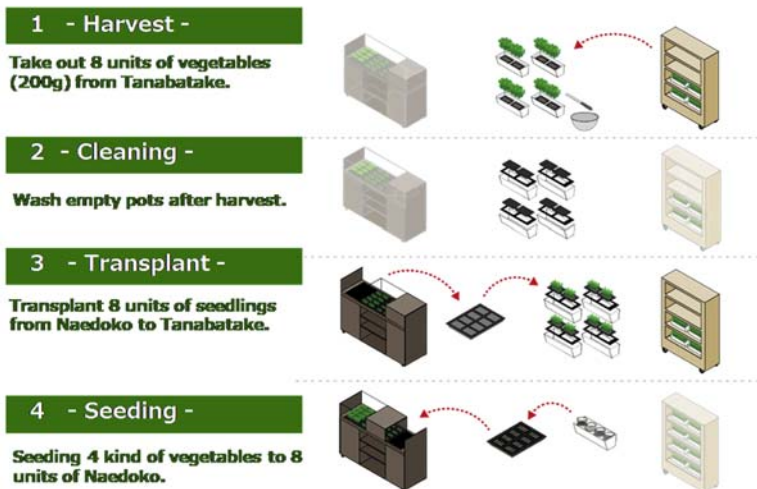
6.3.3 Schools and community centers

m-PFALs are also used as an educational tool (Figs. 6.5 and 6.6) and as a communication tool (Fig. 6.7). While experiencing the fun of raising plants first-hand, school children gain an implicit and integrated understanding of the scientific principles at work in the environment, natural resources, food production, and ecosystems. m-PFALs could become practical tools for lifelong self-learning about diet, the environment, nature, energy, and natural resources. Using the m-PFAL will reinforce people's

**FIGURE 6.2A**

m-PFALs placed at the entrance to Café Agora in Kashiwa, Chiba, Japan. The vegetables are served to the customers. Designed by H. Hara and T. Hatta.

The workflow (Twice a week)

**FIGURE 6.2B**

Sustainable business model of m-PFALs at Café Agora.

**FIGURE 6.3**

m-PFAL built on 11th floor of a stationary shop in Ginza Itoya (left). The produce is used for salad by the restaurant on the 12th floor (center, right).

**FIGURE 6.4**

m-PFAL installed at a shopping center to catch people's attention [Frespo Inage, Inage Ward, Chiba City (H. Hara)].

**FIGURE 6.5**

m-PFAL used as a trial educational tool for extracurricular activities at Irifune Junior High school in Chiba prefecture during 2016–17.

**FIGURE 6.6**

m-PFAL at Miyagi Agricultural High School used as an educational tool for plant production under artificial lighting (H. Hara).

**FIGURE 6.7**

m-PFAL used as a communication tool for collaborative activity between high school students and residents of temporary housing in Miyagi where the earthquake and tsunami struck on March 11, 2011 (H. Hara).

awareness of the vital importance of foods and plants in our environment, of reducing our consumption of natural resources, and of preserving and protecting the environment.

In New York in the United States, plant factories using sunlight and artificial light are increasing in number. Local governments, companies, and schools work together to operate plant factories with students in order to popularize local foods. More than 300 students from public junior high and high schools in the center of New York City (the Bronx, Manhattan, Brooklyn) participate in the program “Teens for Food Justice,” which works to ensure access to fresh, healthy, affordable food ([Teens for Food Justice, 2018](#)).

6.3.4 Hospitals

m-PFALs can also be used at hospitals ([Fig. 6.8](#)). The m-PFAL shown in [Fig. 6.8](#) is located in the lobby of the Sakakibara Memorial Hospital, Tokyo. The vegetables are grown by rehabilitation clients and served

**FIGURE 6.8**

m-PFAL in the lobby of the Sakakibara Memorial Hospital in Tokyo. Vegetables are grown by rehabilitation clients and served to in-patients. Designed by H. Hara and J. Hashimoto.

**FIGURE 6.9**

m-PFAL at the entrance to the main office of Chiba University.

to in-patients. Growing plants can be a type of horticultural therapy for rehabilitation clients. The m-PFAL at the hospital functions as a communication tool among clients and hospital staff such as nurses. Implementation of the m-PFAL is planned as part of the alternative integrative medicine at the hospital.

6.3.5 Offices

It can sometimes be stressful for people to work on a computer all day with no green plants in the office and little chance to chat with colleagues. The m-PFAL shown in Fig. 6.9 functions as an entrance partition. m-PFALs may be useful as a communication tool among colleagues and for relaxing.

6.3.6 Small shops and rental m-PFALs

A company located in Kashiwa displays m-PFALs with a floor area of 3 or 6 m² for rent (price for the smaller one: 50 US\$ per month) at a nearby exhibition site (Fig. 6.10). The m-PFAL can be lifted up by

**FIGURE 6.10**

m-PFAL for rent (50 US\$/month), 2 m wide, 2 or 3 m long, and 2.5 m high (left). A stall-type shop selling PFAL-grown vegetables at the production site (Sankyo Frontier, Nagareyama City, Chiba) (right).

a crane and transported by a small truck. The company also produces and sells vegetables using a larger PFAL at the exhibition site.

6.4 Design concept of m-PFALs

The objective of m-PFALs is to bridge the gap between the use of plants and cultivation from the viewpoint of users, and make these two elements match. The users' situation and needs vary depending on whether the m-PFAL is for a home, restaurant, school, community facility, or office. To create the ideal situation for each case, it is necessary to integrate a design for the users and for cultivation. By achieving this integration not only functionally but also aesthetically, the value of m-PFALs in society is established. The power of design emphasizes the beauty of plants, which inspires the users to grow better plants. This virtuous circle of users and plants should be the basic design concept of m-PFALs.

6.5 m-PFALs connected by the internet

A social experiment project using m-PFALs was launched in 2012 in the Kashiwa-no-ha district of Kashiwa City in Chiba Prefecture, Japan (Fig. 6.11; Kozai, 2013). The project was conducted by the Working Group of the “In-Town Plant Factory Consortium Kashiwa-no-ha,” consisting of Chiba University, Mitsui Real Estate Co., Ltd., Panasonic Corporation, and Mirai Co., Ltd., with the collaboration of local residents acting as end-users for the project.

Objectives. The project was intended to examine (1) how people can grow vegetables in household spaces; (2) the effectiveness of the supply of cultivation advice; (3) the ease of operating the m-PFAL; and (4) the value added from creating a network. The project also assessed the usefulness and commercial feasibility of an exclusively web-based service where m-PFAL growers can ask experts

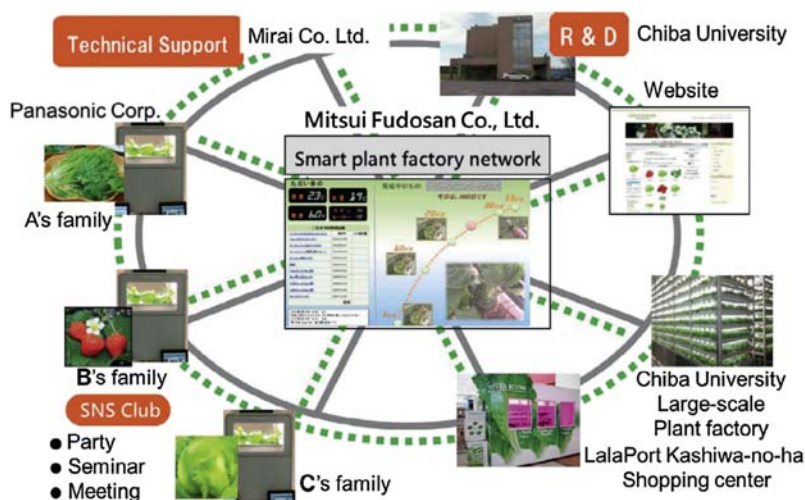


FIGURE 6.11

m-PFAL network as a social experiment.

questions on cultivation management, share information on their own circumstances and experiences, and arrange to exchange the vegetables they have grown.

Through this project, it was found that (1) Internet linking of m-PFALs opened up the possibility of acquiring the latest information on cultivation methods; (2) information on different plant varieties could be downloaded from cloud servers; (3) growers could swap tips on cultivation and food preparation using SNS (social networking sites) such as Facebook and Twitter; and (4) growers could remotely check how their plants were doing using in-built cameras. User activities are further enhanced through get-togethers organized every few months where growers bring their m-PFAL-grown vegetables (Fig. 6.12).

This project is an integral part of making Kashiwa-no-ha in Kashiwa City a “smart and streamlined” community, in keeping with its designation as an “Environmentally Symbiotic City” that is sensitive to preserving green spaces and maintaining the harmony between cities and agriculture. In this district, there are also community gardens and rooftop gardens for growing organic vegetables. This project can be extended to networks that link schools and similar organizations.

6.6 Advanced usage of m-PFAL

6.6.1 Connecting with a virtual m-PFAL

A virtual m-PFAL system incorporating an e-learning function unit can be linked as a network with a real m-PFAL system involving the actual cultivation of plants, having a dual nature. In the virtual system, users can operate the m-PFAL using a simulator that incorporates plant growth, an environment, and a

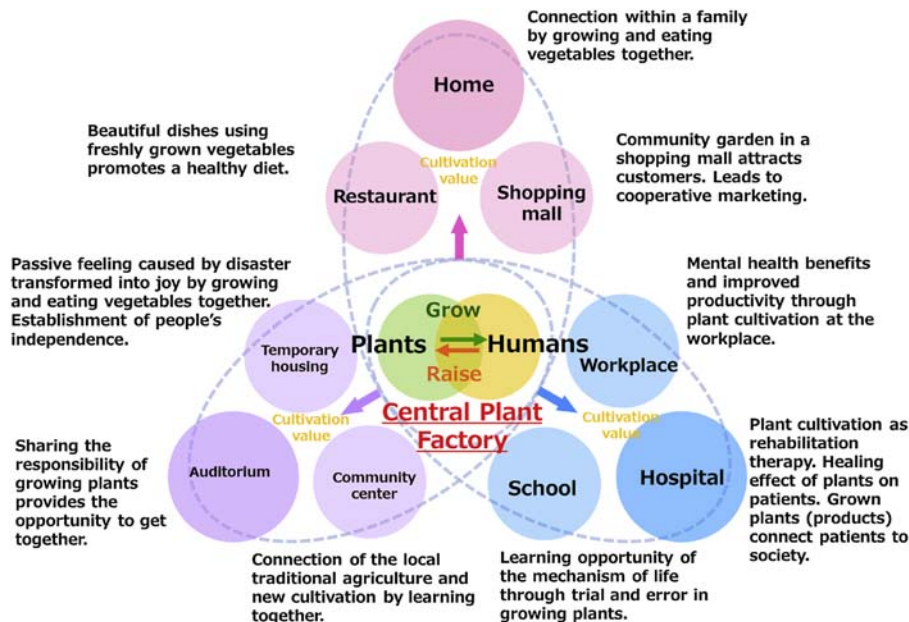


FIGURE 6.12

Various ways of using m-PFAL networks.

business model; after attaining a certain level of proficiency in the simulator, they can transfer their newly obtained knowledge to the real m-PFAL. Or, they can take both approaches in parallel.

6.6.2 Visualizing plant growth as affected by energy and material balance

Since m-PFALs represent almost closed (airtight and thermally insulated) environments, it is possible to quantitatively identify the amount of resources that they consume and produce. Mandatory inputs are the light energy, water, CO₂, and organic fertilizer essential for plant photosynthesis. It is also possible to measure the exact amount of electrical energy required for lighting, air conditioning, and circulation of nutrient solution. At the same time, analysis of the factory's camera images and measurement of plant weight will allow the estimation of plant growth. In addition, by measuring the consumption rates of CO₂, water, electric energy, and light energy, it is possible to estimate the rate of photosynthesis, rate of transpiration, and increase in fresh weight (Li et al., 2012a, 2012b, 2012c). Then, the time courses of plant growth as affected by the rate of input and output can be visualized.

6.6.3 Maximizing productivity and benefits using minimum resources

As people become more familiar with m-PFALs as simplified models of an ecosystem, their ability to maximize food production while maximizing benefits in terms of quality of life will become second nature, as they minimize their environmental impact by reducing their electricity and water consumption, not producing any wastewater, absorbing carbon dioxide, and producing more oxygen for the atmosphere. Along with raising their quality of life will come the joy from supporting the life of living organisms and helping to protect the ecological balance.

6.6.4 Learning the basics of an ecosystem

m-PFALs are simple plant production systems with relatively well-controlled environments, so the environmental effects on plant growth are straightforward. Thus, the ecological relationships between the environment and plants can be understood fairly easily. As the next step, we can connect m-PFALs with other biological systems to learn and enjoy more complicated ecosystems.

6.6.5 Challenges

Challenges for further applications of m-PFALs are: (1) evidence-based experiments for showing the benefits of m-PFALs; (2) collaboration among designers, citizens, and researchers, educators, community planners, and architects in different fields to design, construct, and develop the m-PFALs; and (3) development of “citizen-centered horticulture science”—a new science constructed from the citizens' perspective.

6.7 m-PFALs connected with other biosystems as a model ecosystem

It is possible to foresee networks connected with mushroom culture, aquaculture (fish farming), and aquaponics that raise fish and aquatic plants together (Figs. 6.13 and 6.14). The m-PFAL is an inorganic plant production system, while m-aquaponics is an organic plant production system. By

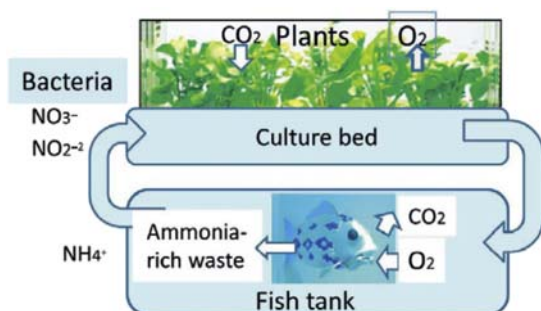


FIGURE 6.13

CO_2 , O_2 , and nitrogen circulation in aquaponics (= aquaculture + hydroponics). Both plants and fish can be harvested. Fish waste is decomposed by bacteria to nitrates and other nutrients for plant growth. Water from the fish tank is pumped up into the culture bed, filtered by the plants and substrate, and then returned to the fish tank.

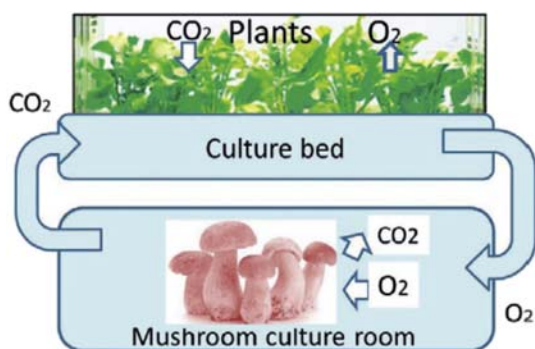


FIGURE 6.14

CO_2 and O_2 circulation in a plant–mushroom culture system. Both plants and mushrooms can be harvested. Plants and mushrooms grow better under CO_2 -enriched and CO_2 -reduced air, respectively.

comparing the two, we can learn the principles of the two biological systems and their differences and similarities.

The small-scale experiences and results could also be applied to large-scale commercial and industrial PFALs. By connecting PFALs with local community energy management systems, these networks can form the infrastructure of a sustainable city. In this way, m-PFALs as well as PFALs will play an important role in the near future to improve the quality of life and communities with less consumption of nonrenewable natural resources and lower emissions of environmental pollutants (Fig. 6.15).

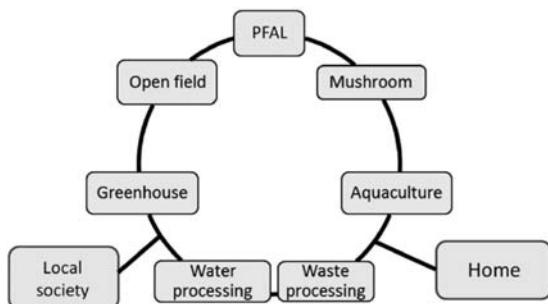


FIGURE 6.15

Combinations of PFALs with other ecosystems.

6.8 Light source and lighting system design

When choosing the type and design of the light source for m-PFALs, we need to consider the physiology and psychology of light perception by humans. This is because the m-PFAL is not only a plant production system but also a green interior. The color rendering index (CRI) of light sources is an important index in the lighting design for humans (http://en.wikipedia.org/wiki/Color_rendering_index). CRI is a quantitative measure of the ability of a light source to faithfully reproduce the colors of various objects in comparison with an ideal or natural (solar) light source (Wikipedia). The CRI value is “100” when the light source functions just as natural light. The color of a plant to the human eye is strongly affected by the CRI of the light source. For example, the color of green lettuce plants under red-dominant LEDs appears as “dark red” and the plants do not look fresh, tasty, and beautiful. The design of the lighting system for the m-PFAL is also important. Other design factors to be considered for the human eye include: (1) color temperature of the light source (cool white or warm white); (2) spatial distribution of the luminous intensity of the light source; and (3) three-dimensional shape and optical characteristics of reflectors.

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Rooftop plant production systems in urban areas

7

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7.1 Introduction

Rooftop plant production (RPP) is the practice of growing plants on top of residential, commercial, and industrial buildings. Plants grown on roofs may be ornamental or edible, require regular pruning and harvesting, or be maintenance free. Many new buildings are being designed with “green roof” space to capitalize on the many proven and potential benefits ([The City of London, 2008](#)), including environmental—stormwater management, heat island reduction, carbon sequestration, and building insulation—and social—community connection, k-12 education, and plant therapy and rehabilitation ([Mandel, 2013](#)).

There are many added benefits for using the roof to grow food crops, including local food production and security, decreased fuel use for transporting food, agricultural jobs training, and improved local economy ([Ganguly et al., 2011](#)). Rooftop agriculture, as a subset of RPP, is gaining popularity within the urban landscape as city dwellers gain interest in local and sustainable food production. This interest is gaining traction as more and more cities lift historical bans on urban agriculture and pass ordinances that allow homeowners, communities, and businesses to grow food in open spaces for more than personal consumption ([Engelhard, 2010](#)).

The rooftop is an ideal landscape for growing plants in dense cities, as it typically has greater exposure to solar energy than the ground below. Further, rooftops are often vacant, except for the mechanical equipment used to condition the building. This combination of factors—sunlight and space—is also why rooftops are good locations for generating on-site solar electricity and solar hot water. The urban PFAL (plant factory with artificial light), like any city building, will have underutilized space that can be used to capture solar energy, either for food production or electricity generation.

7.2 Rooftop plant production

Rooftop production of plants for human consumption may be classified into three categories ([Mandel, 2013](#)): (1) rooftop gardening (small-scale, noncommercial); (2) rooftop farming (medium-scale, commercial); and (3) rooftop agriculture (large-scale, commercial). This chapter focuses on commercial plant production for food, and does not consider the larger context of rooftop agriculture,

which may also include cultivation of animals, bees, fish, fungi, fiber, and feed. Rooftop farming is often characterized by one of the following methods of cultivation: container and raised bed production, continuous row farming, and hydroponic greenhouse growing.

Depending on the method of RPP, there can be many proven benefits. These benefits include mitigation of storm water; reduction of the urban heat island effect; insulation of the roof; and increased biodiversity of pollinators, such as bees, birds, bats, and butterflies ([The City of London, 2008](#)). If carefully designed, RPP can also help to maximize resource use efficiency (RUE) by reusing waste water and waste heat from the building below. RPP has added benefits to PFAL by providing a space to grow crops that are less responsive to the low-light conditions and space constraints of vertical farming. Specifically, the rooftop can be used to cultivate crops that require high light intensities and greater vertical growth, as well as flowering plants that require pollination, root crops that require deeper soil beds, and plants that are more tolerant to heat and variations in temperature and humidity.

Some crop varieties suitable for RPP of PFAL include tomatoes, cucumbers, and peppers. Further, these plants are often cultivated as seedlings within the PFAL and could easily be moved to the roof for full-scale production, thereby reducing the energy and carbon footprint associated with transportation to remote facilities.

Although many cities are beginning to support urban agriculture and green roof construction, local policy and building codes can still be a barrier in many localities ([Engelhard, 2010](#)). Some of the other potential and perceived challenges to overcome when designing an RPP system include structural loads on the roof, accessibility to the roof, utility hookups, leakage and damage to waterproofing, and crop and building maintenance ([The City of London, 2008](#)). However, once implemented, the benefits of the green roof agriculture system will quickly outweigh the challenges that were overcome to build it.

7.2.1 Raised-bed production

Raised-bed production results in moderate yields of food crops that would not be possible inside the PFAL. Raised beds are low-profile structures, typically built out of plastic, steel or wood, and filled with soil for growing plants ([Mandel, 2013](#)). The width and length of raised beds can vary and will depend on the roof dimensions and space availability. Raised beds can also be built to various heights and soil depths, influencing crop selection. Root vegetables and tomatoes require soil depths 12 in. (30.48 cm) or greater; while leafy greens can be grown in shallow depths of 6 in. (15.24 cm). The soil is often a combination of compost, peat moss, and vermiculite or perlite. The compost can be generated on site, from unused plant material (leaves, stems, etc.) at the PFAL, as well as any food waste. Plants may be irrigated by hand or using drip tubes. Raised beds are designed to allow excess water to drain through the soil and out of the bottom to the roof deck. Therefore, the roof should be protected with durable, water-proof material that is designed to channel excess water to a collection system or to the storm drain on the street below. The use of soil and heavy framing materials, such as steel or wood, results in relatively high structural loads, which should be carefully considered. Further, wood is susceptible to rot and should be treated prior to soil infill and planting.

7.2.2 Continuous row farming

Continuous row farming can produce relatively high yields of many crop varieties. Soil is placed directly on the roof structure with continuous row farming, which is most comparable to field farming. Because the planting area is not limited by framing structures, the layout can be flexible and the soil depth varied to accommodate a diverse array of crops in a single growing cycle (Mandel, 2013). Like raised-bed production, soil may be comprised of compost, peat moss, and perlite or vermiculite. However, unlike raised beds, because continuous row farming does not containerize the soil, there may be challenges with soil loss and nutrient leaching during rain events. Providing “edging” around the roof and growing area can help prevent soil loss due to wind and rain. The roof must be designed similarly to a traditional “green roof,” with greater structural capacity and a waterproof membrane that also acts as a root barrier.

7.2.3 Hydroponic greenhouse growing

Of all the RPP systems, growing food in a hydroponic greenhouse will result in the overall highest yields per unit area for any given crop (Mandel, 2013). Hydroponic systems use soilless media to support the plants’ root structure. This media is inert and can consist of rockwool, coconut coir, recycled glass, perlite, sand, and other alternatives. Drip tubes deliver water and nutrients in precise quantities, greatly increasing the water use efficiency (WUE) of the crop. The greenhouse structure itself may be made of glass, rigid plastic (polycarbonate), or plastic film (polyethylene, ETFE, etc.), and sometimes acrylic. The greenhouse is often provided with climate control systems, such as fans, heaters, evaporative cooling, and operable windows, to condition the indoor air and achieve the optimal air temperature, relative humidity, and carbon dioxide levels regardless of outside conditions. The greenhouse is a complex system with design criteria similar to a PFAL. The greenhouse requires the largest initial investment and longest construction period of the three RPP growing methods. The structure can be heavy and susceptible to wind shear, but with close consultation by a structural engineer, these challenges can be managed. Because energy is required to operate the irrigation and climate control systems, the total electricity consumption of the PFAL will increase. However, depending on the location, the greenhouse may be constructed with solar glass, which collects specific wavelengths of sunlight for generating electricity, while transmitting and diffusing other wavelengths into the greenhouse.

7.3 Building integration

RPP presents several opportunities for increasing the sustainability and RUE of the PFAL, including storm water management, reduction of heating and cooling loads in the building below, reducing the building’s heat island effect, and utilizing waste heat from the building and its equipment.

7.3.1 Stormwater management

Stormwater runoff poses many challenges to cities, including flooded streets, strain on sewage conveyance systems and waste water treatment plants, and groundwater pollution of nearby water bodies. Mitigating stormwater has become a prime directive of cities and states as they look to reduce

the impact on aging and undersized sewage systems or simply want to drive sustainable city planning and the construction of green buildings. Several standards and building codes exist now that require or encourage stormwater management, including California's Green Building Code (CALGreen), the US Green Building Council (USGBC) green building certification program LEED (Leadership for Energy and Environmental Design), and the International Green Construction Code (IgCC), to name a few.

RPP systems, commonly known as "green roofs" in the building industry, have become an accepted strategy for mitigating stormwater in cities. Open planting structures, such as raised beds and row farming, help control the flow of rainwater from rooftop to street by absorbing rainwater (Fig. 7.1). For example, an open green roof planting system that covers 80% of the roof can retain up to 40% of rainwater for any given location (Table 7.1). In large rain events, the water not absorbed by planting

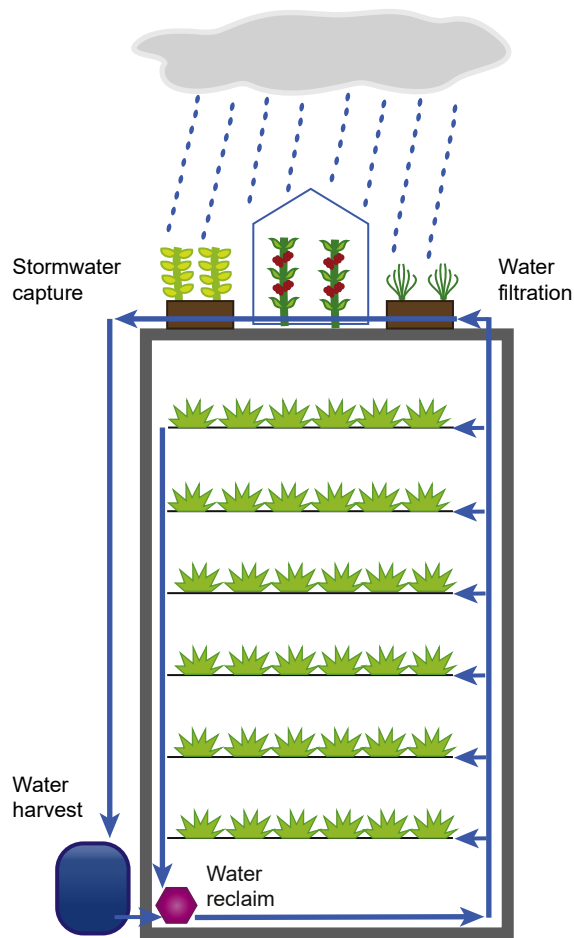


FIGURE 7.1

Water cycle of a plant factory with artificial lighting (PFAL) integrated with a rooftop plant production (RPP) system.

Table 7.1 Potential stormwater capture and solar electric generation on a standard 930 m² roof in selected international cities. Stormwater capture assumes that raised-bed or row farming occupies 80% of the roof surface. Solar electric generation assumes 20% of the roof is available for a 28.1 kW DC-rated photovoltaic system with a fixed tilt of 35 degrees and system loss of 14%.

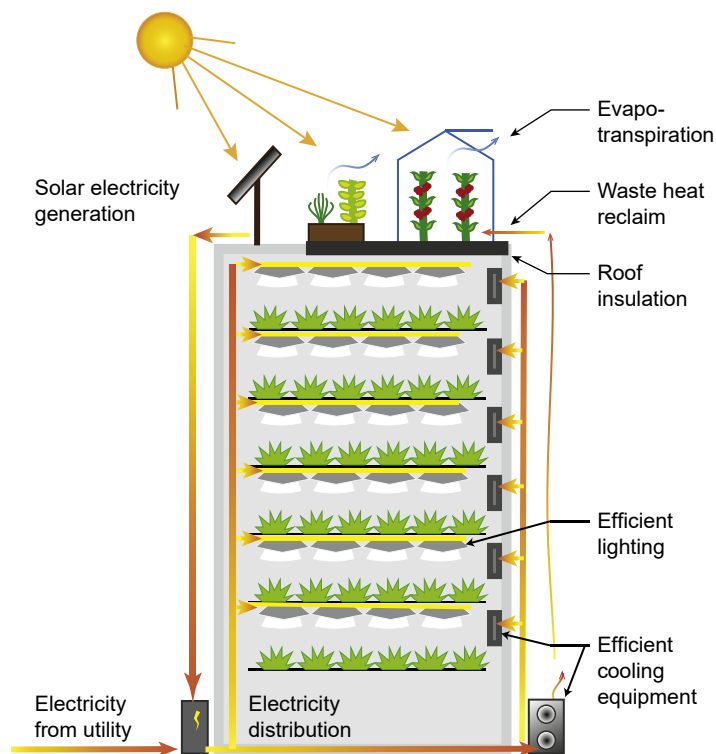
Location	Maximum daily rainfall (kg m ⁻² h ⁻¹)	Maximum stormwater capture (kg m ⁻² h ⁻¹)	Daily average solar radiation (kWh m ⁻² d ⁻¹)	Annual solar electric generation (kWh)
Phoenix	1.06	0.42	6.56	48,600
London	3.29	1.32	3.17	26,000
Barcelona	3.90	1.56	5.17	40,800
San Francisco	4.63	1.85	5.45	44,100
Sydney	5.83	2.33	5.03	39,600
Mexico city	7.63	3.05	4.44	34,000
Tokyo	8.71	3.48	4.51	36,200
Seoul	14.50	5.80	4.01	32,100

systems can be diverted to cisterns and tanks for storage. This water may be filtered for toilet flushing or evaporative cooling and humidification; or it may be stored for future irrigation of the green roof or landscaping. In PFAL with RPP, all stormwater will be used to support plant production, either for irrigation, evaporative cooling, or humidification as needed.

7.3.2 Energy use reductions

Climate control accounts for approximately 15% of all energy consumption in PFALs (Kozai, 2013a). Although this energy consumption is much less than the typical commercial building (about 35%), strategies for reducing HVAC (heating, ventilation, and air conditioning) energy use can translate into significant operational cost savings (ASHRAE, 2013). In the United States, the demand for electricity during peak periods of the day burdens many regional grids as they try to keep up with simultaneous uses of air conditioning, lights, and appliances. Utility companies and some building codes are responding by penalizing consumers for energy use during peak demand periods, typically between 14:00 and 20:00. Therefore, strategies for reducing energy use during these periods can greatly offset energy costs and reduce grid stress (ASHRAE, 2013). Additionally, on-site generation of electricity using rooftop solar panels can power lights, heating and cooling equipment, computers, and other equipment (Fig. 7.2).

A well-designed PFAL will use high-efficiency equipment for operations (Kozai, 2013b), including heat pumps for cooling (and heating), variable-speed motors on pumps and fans for moving water and air, and LEDs for illuminating the crop. The RPP can contribute to the RUE of the PFAL by insulating the roof and obstructing direct solar heat gain through the roof, two factors that will greatly reduce the heating and cooling loads of the grow space below. The plants themselves can mitigate the building's microclimate through evapotranspiration and by absorbing sunlight rather than reflecting it to the

**FIGURE 7.2**

Energy cycle of a plant factory with artificial lighting (PFAL) integrated with a rooftop plant production (RPP) system and rooftop solar electricity generation.

atmosphere above. This combination of factors mitigates the heat island effect caused by many urban buildings that reflect sunlight or emit heat from the building's exterior and dump heat from the building's interior during air conditioning.

Waste heat from inside the building can be further mitigated by recirculating it to the RPP (Fig. 7.2). The waste heat from a PFAL may be generated from primary airstreams (exhaust from the building) or secondary airstreams (heat generated by motors and equipment). Primary airstreams may be ducted directly to a rooftop greenhouse for climate control. Secondary airstreams could be passed through a heat exchanger to produce hot water used for root zone heating of soil beds or hydroponic media, as well as perimeter heating in greenhouses. If a solar hot water system is designed into the building's program, the secondary airstream could also be used to preheat the water storage tank, reheat recirculating water, or provide the primary source of heating when ample sunlight is available.

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Basics of physics and
physiology –
Environments and
their effects

2

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Light sources

8

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8.1 Introduction

Until recently, most of the light sources used for PFALs were fluorescent lamps and high-intensity discharge (HID) lamps (especially high-pressure sodium lamps). According to the latest study by [Shoji et al. \(2013\)](#), 60% of PFALs in Japan use fluorescent lamps (including 6% using cold cathode fluorescent lamps), 27% use LEDs, and 13% use HID lamps. Until just a decade ago, LEDs were used almost exclusively for research on plant cultivation, but are now being used as a light source for practical plant cultivation in PFALs because of their steady price decline and rapid improvement in luminous efficacy [lm W^{-1}], which is a measure of how efficiently an electrical lamp produces visible light.

This chapter examines the fundamentals necessary to understand light sources for PFALs, particularly LEDs, which are attracting increasing attention, and fluorescent lamps, which remain widely used in PFALs. Pulsed lighting effects with LEDs are described briefly along with relevant references. The terminology used in this chapter is based on recently published books by [Mottier \(2009\)](#), [Kitsinelis \(2011\)](#), [IEIJ \(The Illuminating Engineering Institute of Japan\) \(2012\)](#), [Khan \(2013\)](#), and [Japanese Industrial Standards \(JIS\) handbook No. 61 \(2012\)](#).

[Table 8.1](#) presents the relations among luminosity-based, energy-based, and photon-based physical quantities of light environments because some quantities are used in this chapter without explanation.

8.2 Classification of light sources

Electrical lamps used today for general illumination can be classified into three categories according to the principle of light emission: incandescence, discharge light emission, and electroluminescence ([Table 8.2](#)). The principle of incandescence is the same as that of the thermal radiation of a blackbody that radiates or emits light as it is heated. A traditional incandescent lamp is a typical example of one that emits light through incandescence. Discharge light emission refers to the emission of light by transitioning an electron of an atom which has been excited by an electric discharge, from a higher energy state to a lower energy state (mostly to the ground state). Fluorescent lamps and high-pressure sodium lamps emit light through discharge light emission. The third mode, electroluminescence, refers

Table 8.1 Luminosity-, energy-, and photon-based physical quantities with SI units describing the light environment.

Relations	Luminosity basis	Energy basis	Photon basis
A	Luminous intensity [cd]	Radiant intensity [W sr ⁻¹]	Photon intensity [mol s ⁻¹ sr ⁻¹]
$A \cdot \text{sr}$ $= B$	Luminous flux [cd sr] = [lm]	Radiant flux [(W sr ⁻¹) · sr] = [W]	Photon flux [(mol s ⁻¹ sr ⁻¹) · sr] = [mol s ⁻¹]
$A \cdot \text{sr} \cdot \text{s}$ $= B \cdot \text{s}$	Quantity of light [lm s]	Radiant energy [W s] = [J]	Photon number [(mol s ⁻¹) · s] = [mol]
$A \cdot \text{sr} \cdot \text{m}^{-2}$ $= B \cdot \text{m}^{-2}$	Illuminance [lm m ⁻²] = [lx]	Irradiance [W m ⁻²]	Photon flux density (Photon irradiance) [(mol s ⁻¹) · m ⁻²] = [mol m ⁻² s ⁻¹]

to light emission caused by application of an electric field to a material. Of lamps in this category, LEDs have received the greatest attention for use in PFALs.

8.3 Light-emitting diodes

The following fundamentals must be understood when using LEDs for plant cultivation: (1) general benefits, (2) outline of the light-emitting mechanism, (3) configuration types, (4) basic terms expressing electrical and optical characteristics, (5) electrical and thermal characteristics in operation, (6) lighting and light intensity control methods, (7) lesser-known benefits and disadvantages related to use, and (8) LED modules with different color LEDs for PFALs. These items are explained below, together with (9) pulsed light and its effects, because pulsed light is often included in discussions on light sources for PFALs. Lastly, the current state of standardization of the description of LED luminaire performance for plant cultivation is introduced briefly.

8.3.1 General benefits

Generally speaking, LEDs offer advantages over incandescent, fluorescent, and HID lamps: they are robust; produce a stable output (immediately after an electric current flows); are long-lived, compact, and lightweight; instantaneously turn on; and allow the light output to be easily controlled. Moreover, the spectral distribution of emitted light can be controlled with a light source comprising several color types of LEDs. The last point is described at greater length in the section “Lesser-known benefits and disadvantages related to use.”

Table 8.2 Light emission principles and corresponding major electrical lamps and devices.

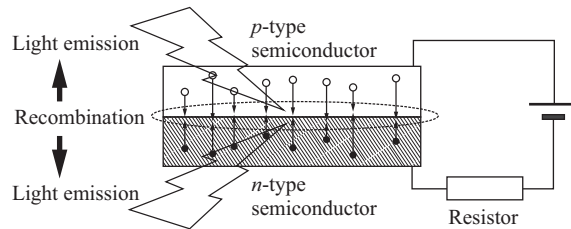
Light emission principle	Electrical lamps/devices
Incandescence	Incandescent lamps Halogen incandescent lamps
Discharge light emission	Low-pressure discharge lamps Low-pressure sodium lamps Fluorescent lamps Preheat fluorescent lamps Rapid-start fluorescent lamps High-frequency fluorescent lamps Cold cathode fluorescent lamps High-pressure discharge lamps High-pressure mercury lamps Metal halide lamps High-pressure sodium lamps High-pressure xenon lamps
Electroluminescence	Intrinsic electroluminescence devices Inorganic electroluminescence devices Injection electroluminescence devices Light-emitting diodes Organic electroluminescence devices

8.3.2 Outline of the light-emitting mechanism

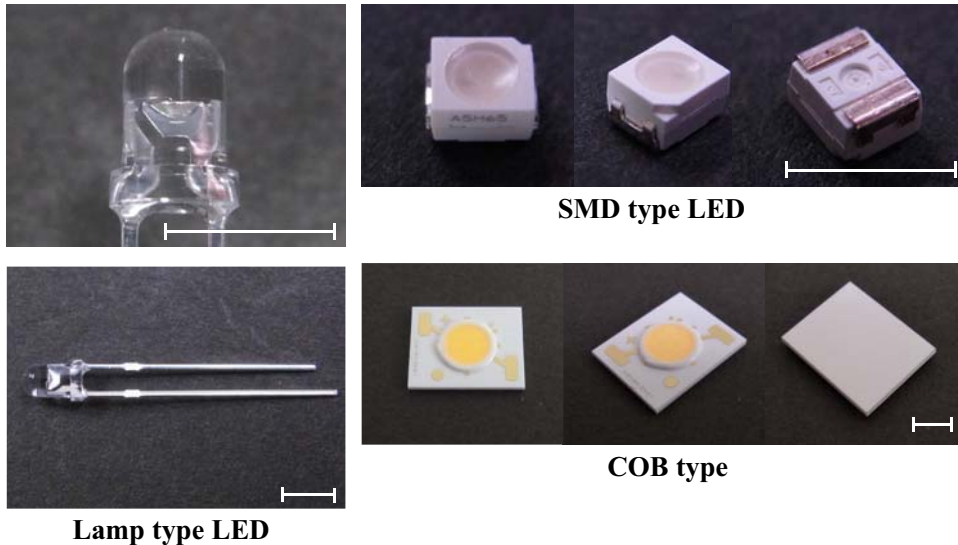
An LED is a semiconductor diode formed by contacting p -type and n -type materials. By applying an appropriate forward voltage to the diode to move holes (having a positive electrical charge) in the p -type material side and electrons (having a negative electrical charge) in the n -type material side toward the other side, the holes and electrons can recombine in the junction. The hole–electron recombination produces a photon, which has energy equivalent to the amount of energy that the electron released by transitioning when recombined. Light is emitted from LEDs in this manner (Fig. 8.1).

8.3.3 Configuration types

The lamp type (or round type, recently also called “through hole” or “thru-hole” type), surface mount device (SMD) type (or surface mount type), and chip-on-board (COB) type are the major configurations for LEDs (Fig. 8.2). The COB type LEDs are categorized into the high-power LEDs, which are capable of producing a large luminous flux from a relatively small light-emitting area. Fig. 8.3 shows the arrangement of lamp type LED components.

**FIGURE 8.1**

LED light emission from the junction of p -type and n -type semiconductors when electricity is supplied. Open and solid circles respectively denote holes (positively charged) and electrons (negatively charged).

**FIGURE 8.2**

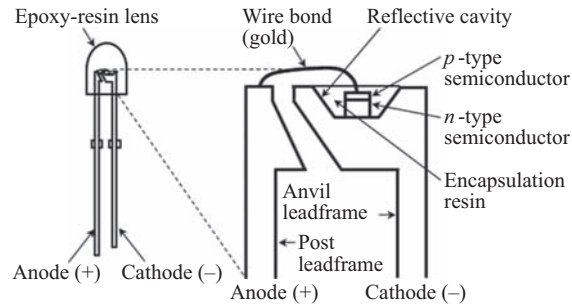
Lamp type (NSPB310B; Nichia Corp.), surface mount device (SMD) type (NESG064; Nichia Corp.), and chip-on-board (COB) type (NTCWT012B-V3; Nichia Corp.) LEDs. White bars indicate a scale of approximately 5 mm.

8.3.4 Basic terms expressing electrical and optical characteristics

Basic terms expressing electrical and optical characteristics of LEDs include the following:

Forward current [A]: Electrical current flowing through an LED from the anode to the cathode. An LED only emits photons/light in forward-bias. In an LED specification sheet, a rated maximum forward current and rated maximum “pulse” forward current are generally described.

Luminous intensity [cd]: This is defined as the luminous flux [lm] emitted into a solid angle [sr] of space in a specific direction (normally the optical axis direction as for LEDs, at which the value

**FIGURE 8.3**

Schematic diagram of a lamp type LED.

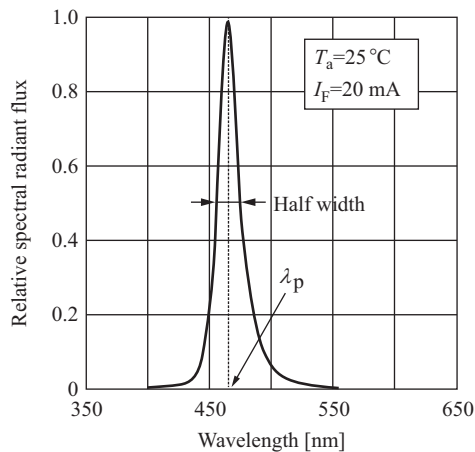
shows the maximum). Regarding LEDs with peak wavelength outside the visible wavelength range, radiant intensity [W sr^{-1}] is used.

Radiant flux/total radiant power [W]: The amount of radiant energy [J] emitted per unit time [s].

Peak wavelength [nm]: The wavelength at which the spectral radiant flux [W nm^{-1}] in the spectral radiant flux distribution curve (spectrum) of an LED is the maximum (Fig. 8.4).

Half width [nm]: The width of the spectral radiant flux distribution curve (spectrum) at 50% of the maximum spectral radiant flux. It is a measure of the light monochromaticity (Fig. 8.4).

Viewing half angle [$^\circ$]: The angle from the LED optical axis (at 0°), at which LED radiant intensity [W sr^{-1}] is the maximum, to which the radiant intensity is reduced to half the maximum value at 0° .

**FIGURE 8.4**

Peak wavelength (λ_p) and half width using a sample spectral distribution of a blue LED (NSPB310B; Nichia Corp). The figure was redrawn from the specification sheet.

8.3.5 Electrical and thermal characteristics in operation

LEDs have common operating characteristics that must be well understood when using LEDs for both plant production and research on the effects of the light environment. The major characteristics are as follows:

- (a) The electric current flowing through an LED increases exponentially with increasing voltage applied to the LED (Fig. 8.5A).
- (b) The relative spectral radiant flux emitted from an LED (and also relative luminous intensity) is roughly proportional to the electric current flowing through the LED when the ambient temperature is constant (Fig. 8.5B).
- (c) Even if the electric current flowing through an LED is constant, the relative spectral radiant flux emitted from the LED (and also relative luminous intensity) decreases with increasing ambient temperature (Fig. 8.5C).
- (d) The maximum forward current allowed (allowable forward current) drops sharply when the ambient temperature increases beyond a certain temperature (typically around 40°C). A maximum ambient temperature exists for the use of LEDs (typically around 80°C) (Fig. 8.5D).

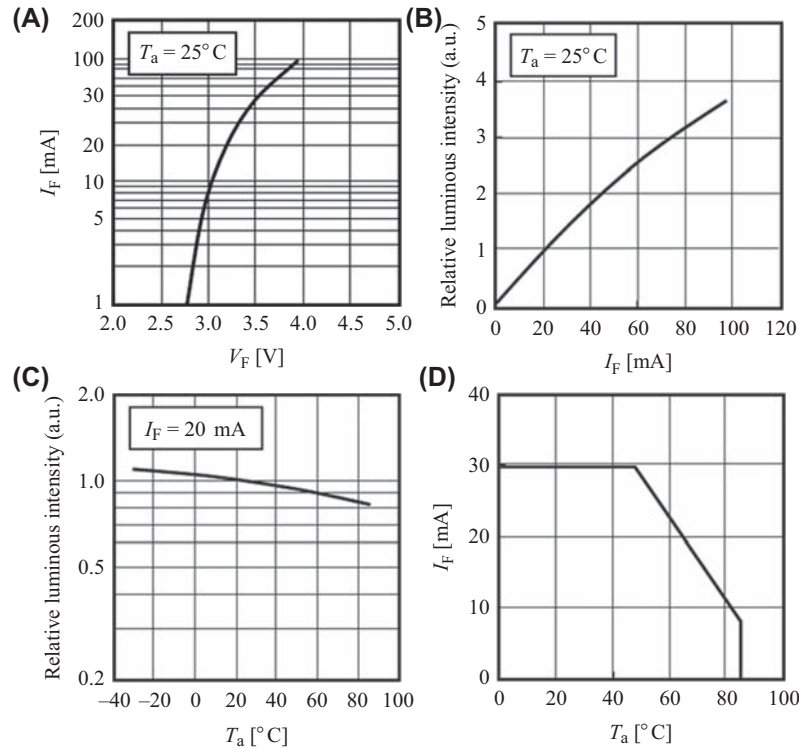
8.3.6 Lighting and light intensity control methods

Two lighting methods are used for plant cultivation in respect of “truly” or “apparently” continuous light during the photoperiod. The most common method is “truly” continuous lighting, in which light is emitted continuously “in a strict sense” during the photoperiod. The other is intermittent lighting, in which light is emitted intermittently in a short time cycle. Although there is no clear definition, intermittent lighting is sometimes designated as pulsed lighting, especially when the one-cycle time (light-on time period plus light-off time period) is less than or equal to 1 s. An LED can produce pulsed light with a light-on and light-off cycle of less than 10 μ s.

Simple and general methods for controlling light intensity (radiant flux in the strict terminology) or dimming an LED include controlling the electric current flowing through the LED. This is called constant-current operation. Constant-voltage operation is a similar method, but it can be done only under the condition of constant temperature of both the LED chip and ambient air. Another method of controlling light intensity is so-called pulse width modulation (PWM). In this method, an LED is repeatedly turned on and off at extremely short intervals by applying and breaking a constant electric current flowing through the LED, causing the LED to produce light intermittently. The pulse width is the time period during which current is applied and the light is on. The percentage of the light-on time period to the one-cycle time period is called the duty ratio (%). A change in the duty ratio results in an increase or decrease in radiant flux from the LED. At 50% duty ratio, the LED will emit almost half the radiant flux that it does at 100% duty ratio. Intermittent light with a light-off time period shorter than a certain level is perceived by the human eye as continuous light.

8.3.7 Lesser-known benefits and disadvantages related to use

An important but less widely recognized benefit of using LEDs as a light source for PFALs is that LEDs offer great flexibility for producing various light environments compared to conventional lamps. For instance, a light source having several types of LEDs with different peak wavelengths can produce light of which the spectral radiant flux can be varied with time. Such light source systems have been

**FIGURE 8.5**

Common electrical and thermal characteristics of a white LED (NSPW310DS; Nichia Corp.) in operation: (A) relationship between forward voltage (V_F) and forward current (I_F), (B) effect of forward current on relative luminous intensity, (C) effect of ambient air temperature (T_a) on relative luminous intensity, and (D) allowable forward current (I_F) with ambient air temperature (T_a). The figures were redrawn from the specification sheet.

developed for research purposes with 5 (Fujiwara et al., 2011; Yano and Fujiwara, 2012), 6 (Fujiwara and Yano, 2013), and 32 (Fujiwara and Sawada, 2006; Fujiwara and Yano, 2011; Fujiwara et al., 2013) types of LEDs for advanced control of the light environment. Such LED light sources are ideal for conducting research on controlling the light environment to improve plant production in PFALs.

The greatest disadvantage of using LEDs for PFALs is the high initial cost for a set of LED light sources and the luminaire (“luminaire” refers to the entire electric light fitting, including all components needed to mount, operate, and protect the lamps) compared to conventional lamps. This disadvantage will take time to overcome.

8.3.8 LED modules with different color LEDs for PFALs

LED modules with different color LEDs (strictly speaking, LEDs that emit light with different relative spectral power distributions) are used in some PFALs. The most common combination is a blue LED

with a peak wavelength (λ_p) of around 460 nm and a red LED with λ_p of around 660 nm. A combination of a red LED and phosphor-converted white LED (made of a blue LED chip coated with a yellow phosphor) is also used for LED modules in a PFAL. An LED module incorporating blue, red, and far-red LEDs is already being used for commercial production of lettuce seedlings in the Netherlands. A multicolor LED module that has green, violet, or ultraviolet LEDs in addition to blue and red LEDs could be used in a PFAL if such a module is shown to improve plant growth and/or increase nutritional and functional ingredients that are beneficial to human health. If asked to choose a single-chip LED for plant production, the author would select a phosphor-converted white LED with a spectral power distribution similar to that of sunlight at ground level.

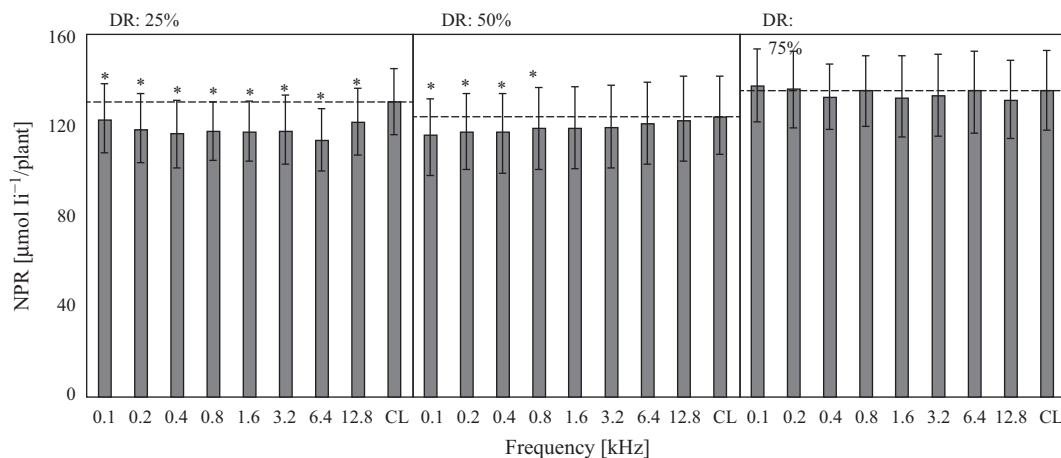
8.3.9 Pulsed light and its effects

An LED can be turned fully on and fully off extremely rapidly; the response time is less than 100 ns. For that reason, LEDs are widely used for investigating the effects of pulsed light on plant photosynthesis and growth. [Tennessen et al. \(1995\)](#) measured the net photosynthetic rate (NPR) of tomato leaves in continuous light and compared the results with those for pulsed light with the same average PPFD ($50 \mu\text{mol m}^{-2} \text{s}^{-1}$) at a duty ratio of 1% from red LEDs. The results showed that NPRs were similar during continuous light and pulsed light at frequencies (reciprocal of the cycle time period) greater than 0.1 kHz. However, at 5 Hz, NPR was half that measured in continuous light. [Jishi et al. \(2012\)](#) reported a similar result: no combination of frequency (0.1–12.8 kHz) and duty ratio (25%–75%) showed significantly greater NPR in cos lettuce plants than in continuous light when irradiated from white LEDs at an average PPFD of $100 \mu\text{mol m}^{-2} \text{s}^{-1}$ (Fig. 8.6). [Sims and Pearcy \(1993\)](#) and [Pinker and Oellerich \(2007\)](#) reported no positive effect of pulsed light on growth rate in *Alocasia* plants and *Amelanchier* and *Tilia* shoots in vitro, respectively. In contrast to those studies, [Mori et al. \(2002\)](#) observed 1.23 times greater NPR and relative growth rate (weight increase rate divided by weight) in lettuce plants under a combination of 2.5 kHz frequency and 50% duty ratio than in continuous light when irradiated from white LEDs at an average PPFD of $50 \mu\text{mol m}^{-2} \text{s}^{-1}$. It seems that pulsed light generally does not promote photosynthesis or plant growth as long as the spectral photon flux density (or spectral irradiance) is constant with time when irradiated, and the average PPFD is the same for pulsed light and continuous light. A recently published series of papers ([Jishi et al., 2015, 2017](#)) has described detailed mechanisms of instantaneous and time-mean leaf photosynthetic rate under pulsed light.

8.3.10 Description of LED luminaire performance for plant cultivation

Recently, the market has provided a large variety of LED luminaires for plant cultivation. However, to select an appropriate or desirable LED luminaire among them is not easy for greenhouse growers and plant factory managers because few manufacturers and suppliers provide the necessary performance data of luminaires for plant cultivation. Furthermore, no established standards describe the LED luminaire performance.

The American Society of Agricultural and Biological Engineers has recognized the plant growth community's need for a standardization committee for developing LED horticultural lighting standard documents. It formed the new Plant Growth LED Lighting Committee in early 2015 ([Jiao, 2015](#)) and released a standard designated as "Recommended methods for measurement and testing of LED

**FIGURE 8.6**

Net photosynthetic rate (NPR) of the aerial part of cos lettuce with different combinations of duty ratio (DR) and frequency of pulsed light from white LEDs. Dashed lines represent NPRs in continuous light (CL) from white LEDs. Bars represent S.E. ($n = 6$). Means with an asterisk are significantly different from that obtained on the same day in continuous light (paired t test, $P < .05$) (Jishi et al., 2012).

products for plant growth and development” in September 2018. A copy of the standard document can be downloaded for a fee. Both et al. (2017) have presented an example of a product label for an LED lamp specifically designed for plant growth application. The configuration example is well organized with nine item groups. In my opinion, “photosynthetic photon number” (number of photons with 400–700 nm wavelength) should be used instead of “PAR” (photosynthetically active radiation) in their example because the quantity of “radiation” is categorized in radiometric quantities and is expressed in energy-based units, not in photon-based units, as presented in Table 8.1 and in Fujiwara (2016a).

The Japan Plant Factory Association’s committee on LED lighting proposed a standard description sheet of LED luminaire performance for plant cultivation in 2016 (Goto et al., 2016). The committee publicized its at-the-time latest version in 2018 (Fig. 8.7) through its website (<http://npoplantfactory.org/>). The description sheet requires that 18 items in 6 item groups be filled out. It includes nothing special or novel but it does present a newly proposed term of “photosynthetic photon number efficacy” [$\mu\text{mol J}^{-1}$]; it is defined as the energy-photon (400–700 nm wavelength) conversion efficacy (Fujiwara, 2016b).

8.4 Fluorescent lamps

Shoji et al. (2013) reported that 60% of PFALs in Japan use fluorescent lamps (including cool cathode fluorescent lamps) as a light source. However, newly constructed PFALs in Japan tend to use LEDs rather than fluorescent lamps. Regarding shape, tubular fluorescent lamps are exclusively used in PFALs. There is no report on the starting types (preheat, rapid-start, high-frequency, or cold cathode)

Description of LED luminaire performance for plant cultivation

Manufacturer	
Trade name	
Model number	
Measurer	
Measurement date	
Respondent's contact name	
Date of description	
Change record	

Item group	Item	Unit	Write-in column	Measuring instrument /method	Remarks
Measuring condition	Temperature of ambient air	°C			
Electric power	Power-supply current type	—			AC/DC
	Rated voltage	V			
	Rated current	A			
	Rated power consumption	W			Rated power consumption for lighting and controlling light output. Separate description of rated power consumption for each component is acceptable.
Spectral characteristics	Spectral photon flux distribution	To be shown separately ¹			Wavelength: 300–800 nm X-axis: wavelength [nm] Y-axis: spectral photon flux [$\mu\text{mol s}^{-1} \text{nm}^{-1}$]
	Spectral radiant flux distribution	To be shown separately ¹			Wavelength: 300–800 nm X-axis: wavelength [nm] Y-axis: spectral radiant flux [W nm^{-1}]
	Photosynthetic photon flux (PPF)	$\mu\text{mol s}^{-1}$			Wavelength: 400–700 nm
	Photosynthetic radiant flux	W			Wavelength: 400–700 nm
	Luminous flux	lm			
	Color temperature	K			Only for white LEDs
	Color rendering index	—			Only for white LEDs
Spatial distribution characteristics	Spatial distribution curve of luminous intensity	To be shown separately ¹			If possible, a spatial distribution curve of "photosynthetic photon intensity" is preferable to that of "luminous intensity".
Efficacy/Efficiency	Photosynthetic photon number efficacy	$\mu\text{mol J}^{-1}$			Wavelength: 400–700 nm
	Photosynthetic radiant energy efficiency	J J^{-1}			Wavelength: 400–700 nm
	Luminous efficacy	lm W^{-1}			
Maintainability	Lifetime from the viewpoint of PPF decrease	h			Time to 90% of the initial PPF
	Dust-proof and water-proof characteristics	—			IP code ("IP" followed by a two-digit number)

¹Graph and measured data files should be submitted.

FIGURE 8.7

Standard description sheet of LED luminaire performance for plant cultivation (Japan Plant Factory Association's Committee on LED Lighting, 2018; <http://npoplantfactory.org/>).

of fluorescent lamps used, or their relative percentages. Presumably rapid-start and high-frequency types account for the greatest percentage of fluorescent lamps used in PFALs.

The (1) general benefits, (2) tubular fluorescent lamp configurations, (3) outline of the light emission mechanism and process, and (4) relative spectral radiant flux of light emitted from a fluorescent lamp are outlined below.

8.4.1 General benefits

Fluorescent lamps offer no clear single advantage over other lamps including LEDs. Nevertheless, tubular fluorescent lamps are still one of the most appropriate light source at present for PFALs when considering all the factors of lamp and luminaire prices, rated life, luminous efficacy, ready availability, and lighted lamp surface temperature.

8.4.2 Configuration of tubular fluorescent lamps

A tubular fluorescent lamp generally comprises a glass tube (mostly 25 mm diameter, several lengths available according to the required luminous flux) coated inside with a fluorescent material (phosphor), two tungsten electrodes at the two inside ends that are coated with an electron-emissive material, a small amount of mercury, and low vapor-pressure inert gas (mostly argon) enclosed in the glass tube.

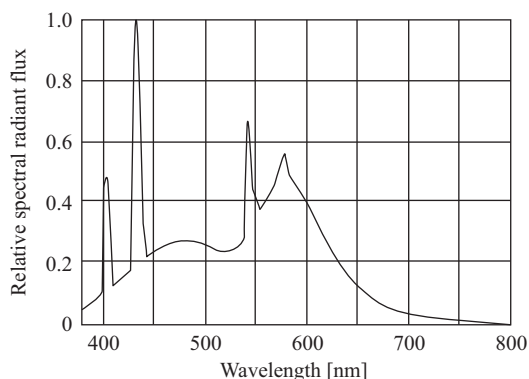
8.4.3 Outline of the light emission mechanism and process

The light emission from a fluorescent lamp is the result of electron-transitioning of mercury atoms that have been excited by an electric discharge generated by the application of an alternating voltage to the electrodes. Therefore, the principle of light emission of a fluorescent lamp is classified as the discharge light emission. Incidentally, based on the fluorescence process taking place on the fluorescent material, the light emission of a fluorescent lamp is classified as photoluminescence.

Light is produced by a fluorescent lamp through the following processes: (1) electricity is supplied to the electrodes through ferrule pins (metal fittings), (2) thermal electrons are emitted from the electrodes, (3) the thermal electrons collide with mercury atoms, (4) the mercury atoms radiate ultraviolet light (emission line: 254 nm), (5) the ultraviolet light reaches the fluorescent material coated on the inside of the glass tube, (6) the fluorescent material converts some ultraviolet light into visible light, and (7) the visible light is transmitted through the lamp glass to the outside of the glass tube.

8.4.4 Relative spectral radiant flux of light emitted from a fluorescent lamp

A fluorescent lamp emits broad-wavelength light ranging from ultraviolet to visible light with the emission lines of mercury (365, 405, 436, 546, and 577 nm within visible light) in its spectrum (Fig. 8.8). The continuum spectrum shows light emission from the fluorescent material. Fluorescent lamps with various spectra or relative spectral radiant flux, in which different types of fluorescent materials are used to coat the inside of the glass tube, are commercially available. Several types of fluorescent lamps developed for plant production are also available, although they cost more than general white fluorescent lamps.

**FIGURE 8.8**

Spectral distribution of a tubular daylight white fluorescent lamp (FLR110HN/A/100; Toshiba Lighting & Technology Corp.). The figure was redrawn from the specification sheet.

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Plant responses to light

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9.1 Physical properties of light and its measurement

9.1.1 Physical properties

Light is electromagnetic radiation, including both visible and invisible wavelengths (Fig. 9.1). The shorter the wavelength, the greater the energy. The wavelength of visible light ranges from approximately 380 to 780 nm, which is what human eyes perceive. Visible light is very important to plants because it coincides roughly with photosynthetically active radiation (PAR, 400–700 nm). For solar radiation, 97% is within the 280–2800 nm range. Of this, 43% is visible light, which is useful for plant growth, 4% is ultraviolet, and 53% is infrared, which produces heat energy. However, only electric lights are used in PFALs. Wavelengths are classified as shown in Table 9.1; each waveband has its own importance or function.

Light possesses two contradictory properties: it can be observed as a wave phenomenon and yet it also acts as discrete particles called photons. A photon is the smallest particle of light, or a single

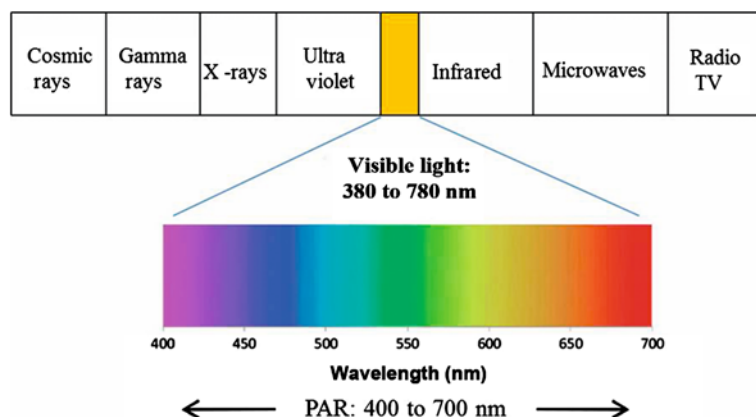


FIGURE 9.1

The electromagnetic spectrum.

Table 9.1 Wave properties of light and their importance.

Classification	Wavelength (nm)	Importance
Ultraviolet	100–380	
UV-C	100–280	Disinfecting
UV-B	280–320	Photomorphogenesis (e.g., sun burn, inhibition of stem elongation), plant secondary metabolite production, disorder and damage
UV-A	320–380	Photomorphogenesis (e.g., sun burn, inhibition of stem elongation), plant secondary metabolite production, photoreactivation
Visible	380–780	
Photosynthetically active	400–700	
Physiologically active	300–800	Photosynthesis, photomorphogenesis (e.g., seed germination, seedling de-etiolation, shade avoidance response, hypocotyl and root phototropism, circadian oscillation, reproduction response), and plant secondary metabolite production
Far-red	700–800 (at the extreme red end of the visible spectrum, between red and infrared light)	Photomorphogenesis (e.g., seed germination, seedling de-etiolation, shade avoidance response, and reproduction response), photosynthesis (excitation of photosystem I)
Near-infrared	780–2500	Heat
Infrared	2500 +	Heat

quantum of light. Unlike other environmental factors such as temperature, humidity, and CO₂ concentration, light varies in at least three dimensions: quantity, quality, and duration. When electric lights are used in a PFAL, the lighting cycle, which affects plant growth and development, can be readily changed. Basically, light influences plants in two ways: providing energy or a quantum source and acting as an information medium. As an energy source, the light energy, or photons of light, is captured by plants and a proportion (up to 10%) of photons captured by plants is converted to chemical energy (carbohydrates) through photosynthesis. Most of the light energy or photons captured by plants is converted into heat energy. As an information medium, light is involved in regulating various growth and development processes such as photomorphogenesis and photoperiodism. Photoreceptors in plants function as light sensors and provide plants with information on subtle changes in light composition in the growing environment and control physiological and morphological responses independent of photosynthesis.

9.1.2 Light measurement

There are three systems to measure light, as shown in Table 9.2. The preferred measurement system is quantum, since this system expresses a number of photons (or quanta) of light incident on a unit area (m²) per unit time (second). A quantum sensor is designed to measure light only in the PAR waveband.

Table 9.2 Three light measurement systems.		
Measurement system	Definition	Units
Photonmetric (quantum)	Number of photons per unit area per unit time in a defined waveband, typically from 400 to 700 nm	$\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$
Photometric	Capacity of producing a visual sensation	lx; footcandle $10.8 \text{ lx} = 1 \text{ footcandle}$
Radiometric	Absolute amount of energy	$\text{W} \cdot \text{m}^{-2}$

The photometric system evaluates light according to its capacity to produce a visual sensation. A photometer measures the brightness of light to the human eye with its peak at 555 nm (Fig. 9.2), while the wavelengths in the far-red ($>700 \text{ nm}$) or ultraviolet ($<400 \text{ nm}$) range appear dim to human eye. Therefore, a photometer is not suitable for evaluating the light environment for plant production. The radiometric system evaluates light based on the absolute amount of energy per unit area per unit time (W m^{-2} or $\text{J m}^{-2} \text{ s}^{-1}$). Table 9.3 lists the approximate conversions for different lamp types, quoted from Thimijan and Heins (1983). These are approximate values because the spectral output of sources varies with individual luminaires, lamps, and ballasts, and their hours of use. Conversions for LEDs are not included in this table because the spectral output varies largely among different LEDs.

In addition to instantaneous light intensity, the total amount of light received by plants in a day or daily light integral (DLI) is closely related to plant growth, development, and quality. DLI is the amount of photosynthetic photons received (by a surface) each day and is expressed as moles of light (mol) per square meter (m^{-2}) per day (d^{-1}), or: $\text{mol} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$. In a PFAL, light intensity or

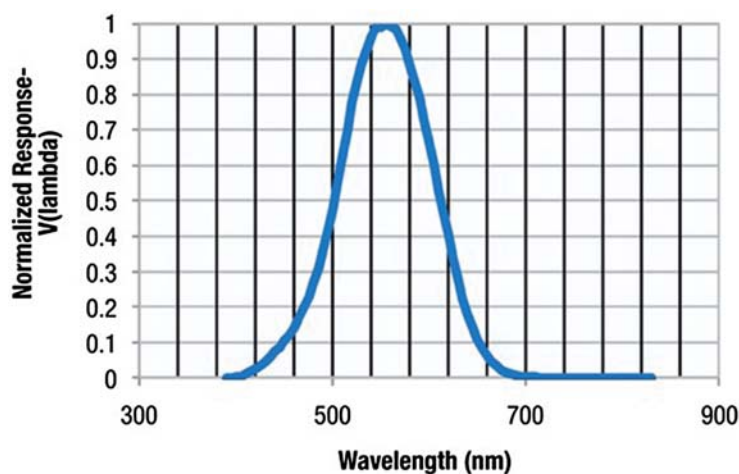


FIGURE 9.2

The human eye's response to different wavelengths of light. Green light generates a maximum response in the eye (peaks at 555 nm). Image reproduced from www.digikey.com.

Table 9.3 Mixed conversion among light sources.				
Light source	$\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$	$\text{W} \cdot \text{m}^{-2}$	Footcandle	lx
Solar light	1	0.219 ^a	5	54
High-pressure sodium	1	0.201	7.59	82
Metal halide	1	0.218	6.57	71
Cool-white fluorescent	1	0.218	6.85	74
Incandescent	1	0.200	4.63	50
^a Values vary depending on light source, lamp, ballast, and hours of use. From <i>Thimijan and Heins (1983)</i> .				

photosynthetic photon flux density (PPFD) is usually kept relatively constant, and so DLI can be easily calculated from the PPFD and photoperiod.

As light technology has advanced quickly in recent years, LEDs are increasingly being used in PFALs. When PPFD under LEDs is measured using quantum sensors, especially for narrowband LEDs, spectral errors occur. This is because the quantum sensor is designed to measure the total number of photons between 400 and 700 nm. When measuring the PPFD of a light source with a different spectrum from that used to calibrate the meter, spectral errors occur. Ideally, spectroradiometers should be used to measure PPFD for LEDs; however, quantum sensors are simple, inexpensive, and easy to use, provided measurement errors are considered.

9.2 Plant responses to light environments

9.2.1 Photoreceptors

Plants perceive light as an energy source for photosynthesis and heat as well as a signal source, which induces various physiological responses. This section introduces the photoreceptors that are mostly related to the role of light as a signal source. Photoreceptors are light-sensitive proteins involved in the sensing of and responding to light in plants. There are two types of photoreceptors in plants, photosynthetic pigments that harvest light energy for photosynthesis and photosensory receptors that mediate nonphotosynthetic light responses. The signals from the photosensory receptors can regulate the expression of genes associated with cell division and enlargement, which can form various tissues such as floral buds and leaf primordia (*Anpo et al., 2018*). Five photosensory systems have been identified up to date, including the phytochromes, cryptochromes, phototropins, members of the Zeitzlupe family, and UV resistance locus 8. Understanding the properties of photoreceptors and their involvements in regulating plant response would deepen our understanding of how plants respond to their light environment and aid in the selection of lighting solutions in PFALs.

Phytochromes

Phytochromes (phys) are primarily red (R, 600–699 nm) and far-red (FR) light-sensing photoreceptors, which are the first identified plant photoreceptors. There are two reversible forms of phys, the biologically inactive form P_r (absorbing R light, peaks at 660 nm) and biologically active form P_{fr} (absorbing FR light, peaks at 730 nm). In general, R light activation of phys may be reversed by FR light. The phytochrome photoequilibrium (PPE), which estimates the proportion of P_{fr} in the total phys

($P_r + P_{fr}$), depends on the spectral distribution of the light source and phytochrome absorption (Sager et al., 1988). The phys family consists of five members, designated phyA to phyE, and individual members of the family have differential, albeit frequently overlapping, photosensory and/or physiological functions in controlling plant responses from seed germination to flowering time, which is stated in Table 9.4 (Li et al., 2011).

Seedling de-etiolation is initiated when seedlings emerge from the soil and perceive light radiation, including hypocotyl growth inhibition, cotyledon expansion, and chloroplast development. Members of phys perform a variety of overlapping functions in regulating plant seedling de-etiolation. PhyA is the primary photoreceptor regulating seedling de-etiolation in responses to FR light, while phyB and phyC respond to R light, and phyB is the predominant phys in response to white and R light (Quail, 2002; Li et al., 2011).

Shade avoidance responses include elongation of stems and petioles, altered flowering time, and increased apical dominance, which elevates the leaves toward light. PhyB is the predominant suppressor of shade avoidance responses in high R:FR ratios, as phyB-deficient plants display a constitutive shade avoidance phenotype, such as elongated petiole and early flowering. The shade avoidance responses enabled by low R:FR ratios can be effectively phenocopied by end-of-day FR (EOD-FR) treatments, which are also regulated by phyD and phyE.

The circadian clock controls many metabolic, development, and physiological processes in a time-of-day-specific manner in both plants and animals. Light signals perceived and transduced by phys and cryptochromes (crys, discussed below) ensure the clock is in tune with the external light/dark cycles.

Cryptochromes

Cryptochromes (crys) are primarily blue (B, 400–499 nm) light photoreceptors. The two members of crys, CRY1 and CRY2, perform overlapping functions in regulating plant responses, including cell

Table 9.4 Different roles of phytochrome family members in seedling and early vegetative development (Li et al., 2011).

Phytochrome members	Primary photosensory activities	Primary physiological roles
phyA	VLFRs ^z	Seed germination under a broad spectrum of light conditions (UV, visible, FR)
	FR-HIRs	Seedling de-etiolation under FR _c ; promoting flowering under LD
phyB	LFRs	Seed germination under R _c
	R-HIRs	Seedling de-etiolation under R _c
	EOD-FR (R/FR ratio)	Shade avoidance response
phyC	R-HIRs	Seedling de-etiolation under R _c
phyD	EOD-FR (R/FR ratio)	Shade avoidance response
phyE	LFRs	Seed germination
	EOD-FR (R/FR ratio)	Shade avoidance response

EOD-FR, End-of-day far-red light; FR_c, Continuous far-red light; HIRs, High-irradiance responses; LD, Long daylight condition; LFRs, Low-fluence responses; R/FR ratio, Red/far-red light ratio; R_c, Continuous red light; ^zVLFRs, Very-low-fluence responses.

elongation, photoperiodic flowering, and stomatal opening. In particular, CRY1 plays a major role in B-light inhibition of hypocotyl elongation, while CRY2 plays a relatively minor one. Similarly, CRY1 stimulates cotyledon expansion in response to both high- and low-fluence conditions, whereas CRY2 regulation is limited to low-fluence conditions (Yu et al., 2010). CRY1 and CRY2 both promote floral initiation (Mockler et al., 2003), and several different mechanisms may be involved, including suppression of CONSTANS degradation, a central gene regulating photoperiodic flowering, activation of transcription activators, and modulation of chromatin remodeling (Valverde et al., 2004; Kumar and Wigge, 2010). Although phototropins are the major photoreceptors regulating stomatal opening, *crys* were found to stimulate stomatal opening, too. Mao et al. (2005) reported that the *cry1 cry2* mutant and CRY1-overexpressing plants exhibited reduced and increased stomatal opening in response to B light, respectively.

In addition to the light responses discussed above, *crys* also regulate chloroplast development and anthocyanin accumulation in plants. It has been shown that CRY1 is the major photoreceptor mediating B light induction of the nucleus-encoded genes expression, which encode plastid proteins required for not only photosynthesis and other functions of plastids, but also components of the plastid transcriptional apparatus (Yu et al., 2010). Therefore, *crys* are considered to play critical roles in chloroplast development during seedling de-etiolation. Meanwhile, the overexpression of the CRY1 photoreceptor resulted in high levels of anthocyanin accumulation, suggesting that CRY1 stimulates the accumulation of anthocyanin (Li and Yang, 2007).

Phototropins

Phototropins (phot) are also B light photoreceptors controlling a range of plant responses including phototropism, chloroplast relocation, and stomatal opening. Two members of phot, phot1 and phot2, exhibit partially overlapping roles in regulating the aforementioned responses.

Phototropism is the directional curvature of organs in response to lateral differences in light intensity and/or quality. Specifically, stems exhibit positive phototropism, or curvature toward the light, while roots show negative phototropism, or curvature away from the light. Both phot1 and phot2 regulate hypocotyl phototropism in response to high light intensities, whereas phot1 solely mediates hypocotyl phototropism under low light intensities. Similarly, chloroplast relocation regulated by phot responds to different light intensities. Under low light intensities, phot1 and phot2 induce chloroplast accumulation movement to the upper cell surface to promote light capture for photosynthesis, while under high light intensities, chloroplasts move away from the site of radiation to prevent photodamage of the photosynthetic apparatus in excess light, which is mediated only by phot2 (Christie, 2007). Stomatal opening in plants is primarily mediated by phot, probably through mediating B light-dependent swelling of individual stomatal guard-cell protoplast, allowing plants to regulate CO₂ uptake for photosynthesis and water loss through transpiration (Briggs and Christie, 2002). Similar to the regulation of phototropism and chloroplast accumulation, both phot1 and phot2 function in mediating stomatal opening, although they might differ in their relative photosensitivity.

Members of the Zeitelupe family

The members of the Zeitelupe family, including ZEITLUPE (ZTL), FLAVIN-BINDING KELCH REPEAT F-BOX 1 (FKF1), and LOV KELCH PROTEIN 2 (LKP2), are another group of B light photoreceptors (Somers et al., 2004). The Zeitelupe family participates in controlling the period of circadian oscillation, regulating photoperiodic flowering, and mediating hypocotyl elongation (Miyazaki et al.,

2015). Somers et al. (2004) reported that *ztl* mutants lengthened the circadian period to 35 h in the dark, 9 h longer than the wild type, while overexpression of ZTL shortened the period to 13 h, which correlated with longer hypocotyls and late flowering. The late flowering caused by enhanced ZTL accumulation was most likely through a strong depression in the levels of CONSTANS and FLOWERING LOCUS T. Similarly, *fkf1* mutants have short hypocotyls under continuous B or R light, while LKP2-overproducing plants have elongated hypocotyls under continuous B, R, or white (W) light.

UV resistance locus 8

The UV-B specific photoreceptor, UV resistance locus 8 (UVR8), initiates UV-B-mediated signaling pathways in response to low levels of UV-B radiation. Under UV-B radiation, UVR8 is translocated from cytosol to nucleus and interacts with COP1 (CONSTITUTIVELY PHOTOMORPHOGENIC 1), resulting in an increase in the expression of HY5 (ENLONGATED HYPOCOTYL 5) and HYH (HY5 HOMOLOG). In turn, HY5 and HYH control expression of a range of key elements for UV-B acclimation, including genes encoding enzymes of the phenylpropanoid pathway (Schreiner et al., 2012). Meanwhile, perception of low UV-B radiation by UVR8 also affects plant morphology, causing growth retardation such as the inhibition of hypocotyl elongation (Jansen and Borman, 2012). Recently, UVR8 was also shown to be involved in regulating thermomorphogenesis, shade-avoidance response, plant immunity, and circadian clock entrainment, underlining the importance of signaling crosstalk among light, clock, hormone, and defense pathways (Yin and Ulm, 2017).

9.2.2 Plant response to light intensity, photoperiod, and daily light integral

In a PFAL, light intensity (PPFD) usually is kept constant, unlike natural sunlight, which varies diurnally as well as seasonably in intensity, duration, and spectral composition. PPFD and photoperiod are two important light conditions in regulating plant growth, development, and nutritional values.

The daily light integral (DLI) represents the total photosynthetic photon flux radiated by a light source in 1 day, and usually has a linear relationship with crop yield in a PFAL. For leafy greens, PPFD in commercial PFALs are in the range of 150–250 $\mu\text{mol m}^{-2} \text{s}^{-1}$ with a photoperiod of 16 h per day, corresponding to DLI of 8.64–14.4 $\text{mol m}^{-2} \text{d}^{-1}$. High DLIs are favorable for improving yield and accumulating secondary metabolites in horticultural crops (Schnitzler and Habegger, 2004; Chang et al., 2008). However, higher DLI increases production cost by increasing capital cost (light fixture numbers) and operational cost (electrical consumption). Therefore, for PFAL, a minimum DLI should be targeted to reduce costs while still achieving a reasonably high yield and quality.

In a study by Zhang et al. (2018) to determine the optimal PPFD in a PFAL, lettuce plants were grown under a range of PPFD of 150, 200, 250, or 300 $\mu\text{mol m}^{-2} \text{s}^{-1}$, provided by fluorescent lamp with red to blue light ratio (R:B) of 1.8 or two types of LED with R:B ratio of 1.2 or 2.2 at two photoperiods (12 h or 16 h per day). Based on yield, quality (nitrate, vitamin C, soluble sugar, and protein and anthocyanin content), and energy consumption, PPFD between 200 and 250 $\mu\text{mol m}^{-2} \text{s}^{-1}$ with photoperiod of 16 h per day under LED light with R:B ratio of 2.2 was the best. By continuously measuring the photosynthetic rates for 48 h of lettuce leaves 2 weeks after transplanting, the plants under PPFD of 300 $\mu\text{mol m}^{-2} \text{s}^{-1}$ had constantly lower net photosynthetic rates than those under 250 $\mu\text{mol m}^{-2} \text{s}^{-1}$. PPFD at 300 $\mu\text{mol m}^{-2} \text{s}^{-1}$ did not have any advantage in enhancing quality traits except for leaf nitrate content, compared to PPFD of 250 $\mu\text{mol m}^{-2} \text{s}^{-1}$. Leaf nitrate content can be

lowered by preharvest continuous lighting (Bian et al., 2016) and by lowering nitrogen level in the nutrient solution.

In our previous study, the effects of five DLI levels of 9.3, 11.5, 12.9, 16.5, and 17.8 mol m⁻² d⁻¹ with a 16 h photoperiod were tested on yield and nutritional values of sweet basil (*Ocimum basilicum*) under an indoor controlled environment (Dou et al., 2018). The results indicated that higher DLIs of 12.9, 16.5, or 17.8 mol m⁻² d⁻¹ led to higher net photosynthetic rate, larger and thicker leaves, and the shoot fresh weight was 54.2%, 78.6%, and 77.9% higher than that at DLI of 9.3 mol m⁻² d⁻¹, respectively. However, no differences in yield were observed among DLIs of 12.9, 16.5, or 17.8 mol m⁻² d⁻¹. The amounts of total anthocyanin, phenolics, and flavonoids per plant were also positively correlated to DLIs (Fig. 9.3). We also conducted another study on sweet basil with a fixed DLI of 12.9 mol m⁻² d⁻¹, created by varying photoperiod (12, 14, 16, 18, or 20 h/d) and PPFD (298, 256, 224, 199, or 179 μmol m⁻² s⁻¹). Except for leaf area, we did not find any differences in yield, photosynthesis, chlorophyll concentration, and other growth parameters, while nutritional quality traits were not determined in this study.

Plant growth responds almost linearly to increasing PPFD under a controlled environment, and the photosynthetic efficiency decreases when a light saturation point is reached. The light saturation point is species specific and is dependent on environmental conditions. For example, there was a linear increase in both leaf fresh weight and dry weight in kale (*Brassica oleracea*) and spinach (*Spinacia oleracea*) as the PPFD increased from 125 to 620 μmol m⁻² s⁻¹ in a growth chamber, while the concentrations of Ca, Cu, K, and Mn in kale plants all decreased at high PPFD due to dilution effects

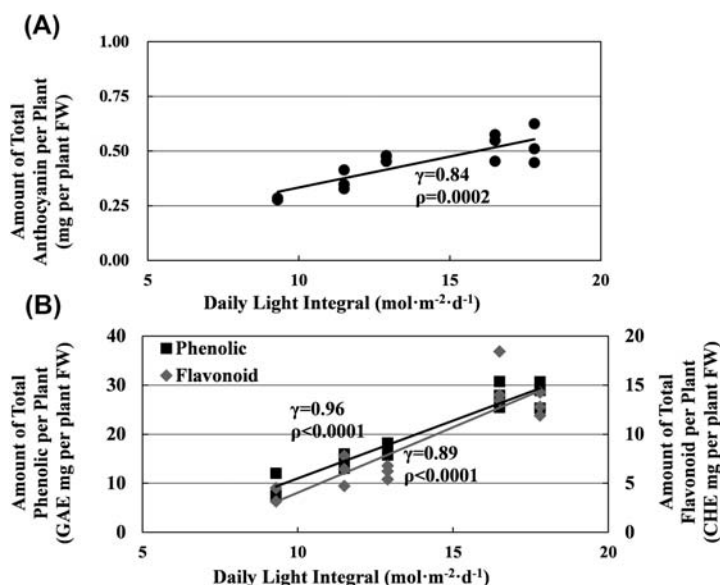


FIGURE 9.3

Correlation between amount of total anthocyanin per plant (A), amount of total phenolic per plant, and amount of total flavonoid per plant (B) with DLIs of green basil “Improved Genovese Compact” grown for 21 days at different DLIs in an indoor controlled environment (Dou et al., 2018).

resulting from increased leaf fresh weight (Lefsrud et al., 2006). However, the shoot and root growth and anthocyanin content of “Kudo” perilla (*Perilla frutescens*) were decreased under PPFD of $500 \mu\text{mol m}^{-2} \text{s}^{-1}$ compared to $300 \mu\text{mol m}^{-2} \text{s}^{-1}$, while the total polyphenol content was increased (Hwang et al., 2014). For leafy greens and seedlings in PFALs, PPFDs are kept in the low linear dose—response range of up to $250 \mu\text{mol m}^{-2} \text{s}^{-1}$ as indicated by our research results (Dou et al., 2018; Zhang et al., 2018; Yan et al., 2019).

Growing plants under a low PPFD for a long photoperiod at the same DLI could reduce the capital costs of a plant factory due to decreased number of light fixtures and requirements for cooling. A number of studies showed that long photoperiod generally increased plant biomass accumulation due to leaf expansion and chlorophyll increase than plants exposed to a high PPFD for a short photoperiod at the same DLI (Adams and Langton, 2005). However, many sensitive species developed physiological disorders such as leaf chlorosis and chlorophyll degradation under an extended photoperiod (Langton et al., 2003; Kang et al., 2013). For instance, the growth and yields of tomato (*Solanum lycopersicum*) and sweet pepper (*Capsium annuum*) plants were decreased, and light injury symptoms were observed in tomato, eggplant (*S. melongena*), potato (*S. tuberosum*), radish (*Raphanus sativus*), and cucumber (*Cucumis sativus*) plants under continuous lighting (24 h photoperiod) (Sysoeva et al., 2010). The reduced growth and yield under extended photoperiod are caused by the leaf inability to export accumulated photosynthates out of the leaf or the destruction of chloroplasts due to some photooxidative stress caused by a long photoperiod (Demers et al., 1998; Ali et al., 2009).

9.2.3 Plant response to light quality

Plants sense and respond to a broad range of light spectra from UV to FR regions, and light quality or light spectrum wavelength significantly affects plant growth, development, morphology, and secondary metabolism. The advancement of LED technology has made it possible to manipulate light spectra to enhance crop yield and nutritional quality. In the past decade, the number of research studies on this topic has increased exponentially worldwide (Bantis et al., 2018). Plant responses to light quality are species and cultivar specific. Depending on environmental conditions, plant responses to the same light quality may be modified by “background” conditions such as DLI. For example, plant responses to certain light quality applied as supplemental lighting in a greenhouse environment would be different from those conducted in an indoor environment. Compared to the effect of light quality on plant growth and morphology, there is relatively limited knowledge on how light quality affects plant secondary metabolite accumulation in various crops grown in PFALs.

Red and blue light

Red (R) light is sensed in plants by phys and regulates responses related to seed germination, stem elongation, leaf expansion, flowering induction, etc., while B light is sensed by crys and phot1, and regulates processes such as seedling de-etiolation, phototropism, chloroplast movement, circadian rhythms, growth of roots, and stomatal opening, etc. However, R and B light act antagonistically in the regulation of leaf size and thickness. B light promotes leaf flattening by enhancing phot1 activity, while R light predominantly promotes branching by activating phyB (Anpo et al., 2018). Thus, careful attention must be paid in determining the balance between R and B light so that plant architecture is regulated in accordance with the intended purpose.

The high efficiency of R and B light on plant photosynthesis and growth is easily understood since they perfectly fit the absorption peaks of chlorophylls. Many companies quickly developed R&B LED lights for PFAL and greenhouse supplemental lighting. Early research indicated that combined R&B light is more effective than monochromatic R or B light for plant growth and monochromatic R or B light may induce physiological disorders in several plant species. For instance, monochromatic R light decreased the F_v/F_m , stomata density, photosynthetic capacity, and impaired growth in cucumber and tomato plants which was defined as the “red light syndrome,” and none of these effects occurred in leaves that were grown under combined R&B light (Hogewoning et al., 2012; Savvides et al., 2011; Trouwborst et al., 2016). This indicated that a certain amount of B light is essential for maintaining normal plant growth. More recent research has shown that full-spectrum white LEDs are more suitable for PFAL, which not only ensures plants receive all the photosynthetically active radiation to optimize growth, quality, and yield, but also allows for easy visual assessment of plants in PFALs for any possible disorder.

Whether for combined R&B or full-spectrum white LEDs, there is no single optimal R:B ratio or B light proportion (BP) that fits all species. For examples, the shoot fresh weight of basil and cucumber plants increased when BP increased from 7% to 59% in combined R&B light, while “Wala” basil plants grown under white fluorescent light (8% BP) had higher plant height and greater shoot fresh weight compared to plants grown under white LEDs (16% BP) (Fraszczak et al., 2014; Hogewoning et al., 2010; Piovene et al., 2015).

Numerous studies have been conducted to evaluate the effects of R and B lights on the accumulation of plant secondary metabolites, and results are contradicting in some cases. Several studies have shown that B light induced the production of anthocyanin and phenolic compounds in various plant species, such as lettuce and sage (*Salvia miltiorrhiza*) (Meng et al., 2004; Li, 2010). Accumulation of anthocyanin and phenolic compounds by B light is attributed to the expression of key enzymes in the phenylpropanoid pathway, including phenylalanine ammonia-lyase (PAL), chalcone synthase (CHS), and dihydroflavonol 4-reductase (Jenkins, 2009). Accordingly, the total phenolic concentration and antioxidant capacity in purple basil and kale sprouts were the highest under B light treatment compared to R and white LED treatments (Qian et al., 2016; Hosseini et al., 2018). In contrast, the rosmarinic acid concentration, the major phenolic compound in basil plants, was two times higher under R and white LED lights than plants grown under B light (Shiga et al., 2009). It was also reported that the anthocyanin concentration of green basil plants was the highest under R light, while the total phenolic concentration in green basil plants and the anthocyanin concentration in purple basil plants were the highest under R₇₀B₃₀ (combined R and B light, in which the R and B light percentage was 70% and 30%, respectively) treatment, compared to B or W light treatments (Hosseini et al., 2018). One of the reasons for contradictory results among studies is thought to be the inconsistent light parameters, such as different light sources and light intensities. Although the mechanism of light spectrum affecting phytochemical biosynthesis is still unclear, it is hypothesized that R and B light share some mechanisms, and their effects are dependent on plant species, plant ages, and phytochemical compounds (Taulavuori et al., 2016).

Red and far-red light

Red and FR lights are important signals to plants and the R:FR ratio affects phys-regulated responses such as seed germination, seedling de-etiolation, shade avoidance, and reproduction responses. Recently, it was reported that the supplementation of FR light with shorter wavelength light (400–700 nm) can balance the excitation between photosystem I (PSI) and PSII, which synergistically

increased photochemistry and photosynthesis (Zhen and Van Iersel, 2017). PSI and PSII operate in series to carry out photochemical reactions, which is preferentially excited by FR and short wavelength light, respectively (Hogewoning et al., 2012). It has been reported that short wavelength light supplemented with FR light significantly increased the quantum yield of PSII in “Green Towers” lettuce plants and increased the leaf area and shoot dry weight in geranium (*Pelargonium hortorum* “Pinto Premium Orange Bicolor”) and snapdragon (*Antirrhinum majus* “Trailing Candy Showers Yellow”) plants (Park and Runkle, 2017). One hypothesis is that the photosynthetic efficiency of plants grown under combined FR and short wavelength light should be increased due to a better balance between the excitation of the two photosystems, while some researchers hypothesized that the whole-plant photosynthetic efficiency will be decreased due to a lower PPFD (Demotes-Mainard et al., 2016; Park and Runkle, 2017; Zhen and Van Iersel, 2017). Further research is needed to better understand the effects of FR light on plant photosynthesis.

Green light

Green (G) light acts as a signal, regulating plant nonphotosynthetic responses such as vegetative growth, anthocyanin accumulation, and flowering initiation via phys and crys (Wang and Folta, 2013). Plant responses to G light is in a manner similar to FR light, and shares a general tendency to oppose B or R light-induced responses (Talbot et al., 2006; Folta and Maruhnich, 2007). For instance, G light inhibited hypocotyl elongation, decreased anthocyanin concentrations, and induced shade growth symptoms in *Arabidopsis thaliana* plants (Zhang and Folta, 2012; Anpo et al., 2018). On the other hand, G light is known as a less effective light for plant photosynthesis compared to B or R light. However, the average relative quantum efficiency value for broadband G light is 0.87, which is slightly lower than R light (0.91) and higher than B light (0.73) (Sager et al., 1988). In addition, while B and R lights are strongly absorbed by the upper level leaves, G light penetrates into deeper plant canopy, which could potentially increase crop yield (Wang and Folta, 2013).

UV light

UV light is commonly considered as a stress factor to plant growth due to the excess excitation energy unavoidably leading to the production of reactive oxygen species in plant organelles, such as chloroplasts, mitochondria, and peroxisomes. Recently, a lot of attention has been directed at using supplemental UV radiation to induce the synthesis of phytochemicals in plants, such as anthocyanins, flavonoids, carotenoids, glutathione, and a broad range of other bioactive metabolites, which provide health benefits in human diets (Bantis et al., 2016; Sakalauskaite et al., 2013). In our previous study, supplemental UV-B radiation increased the concentrations of anthocyanin, phenolics, and flavonoids in green basil leaves by 9%–18%, 28%–126%, and 80%–169%, respectively, and the antioxidant capacity of basil leaves was positively correlated to UV-B radiation doses. However, the supplemental UV-B radiation generally decreased the crop yield in both green and purple basil plants (unpublished data). Therefore, further research is needed to find the balance point between enhanced nutritional quality and yield reduction.

9.3 Conclusion

This chapter described the physical properties and measurements of light, and effects of lighting environments on plant growth, development, and concentrations of phytochemicals. With the

advancements of LED light technology, there is increasing interest in manipulating light intensity and quality to improve biomass productivity and enhance concentrations of bioactive secondary metabolites in leafy herbs and vegetables in PFALs. However, no single light solution fits all scenarios. Optimal light environment varies among species and even cultivars, plant growth stages, specific secondary metabolites, and other environmental conditions such as temperature, nutrients, and CO₂ concentrations. With further advancement in lighting and semiconductor technologies, affordable LED lights that are tunable both in light intensity and quality will be available for researchers and commercial PFALs.

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LED advancements for plant-factory artificial lighting

10

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10.1 Need for CEA of all kinds

Growing food crops without stressful environmental factors (e.g., drought, flooding, extreme heat or cold, growth-limiting light) typically enables shorter production cycles and higher yields per cycle, leading to an order of magnitude higher annual crop-productivity rate on an area-footprint basis for protected cultivation compared to open-field agriculture (Mitchell, 2004), and two orders of magnitude more productive for multitiered indoor crop production (Kozai et al., 2015). Various terms worldwide as “indoor agriculture,” “urban farming,” “vertical farming,” or “plant factories” (PFs), such controlled-environment agriculture (CEA) enterprises have great potential to provide fresh, healthy produce year-round without long-distance transport, especially in view of urbanization and climate change caused by unchecked fossil-fuel use. All platforms of CEA, including greenhouse as well as warehouse-based food production, will play increasingly important roles in feeding a rapidly growing world population as we progress through the 21st century. In fact, it is anticipated that agricultural productivity will have to expand as much as 70% above current production levels over the next 30 years to keep pace with projected increases in food demand worldwide (Agrilyst, 2017). Although the productivity potential of CEA is clear, the heavy up-front capital investments for technology and high operational energy costs to grow crops productively indoors causes the indoor agriculture industry to struggle with near-term profitability and carbon-footprint issues. For this reason, quick-turning leafy greens and culinary herbs with low light requirements are the present crop types of choice for PF crop production in warehouses and converted shipping containers.

10.2 All-important energy costs

Energy costs of production presently require that slower-growing, high-light-requiring, fruiting crops be grown in greenhouses, where at least some of the abundant light needed for plant growth and development can be provided by solar radiation. Technology development and optimization will work itself out for every unique CEA application, but reducing total energy costs in general and energy costs for crop lighting in particular remain a challenge and top priority for CEA worldwide. This is especially true for the PF concept, which relies entirely upon indoor sole-source artificial lighting (SSL). One might think that greenhouses (GHs) have an energy-use advantage over PFs in that they mostly use “free” solar

energy over the course of a year, whereas PF growers typically must pay electrical grid costs for all crop lighting. However, energy costs for seasonal cooling of GHs in the summer and for heating in the winter are high compared to those in insulated warehouses, so with supplemental lighting and heating in GHs in the winter, total energy costs tend to even out between GHs and PFs, at least for quick-turning, low-light-requiring leafy greens. Recent analyses find costs of growing leafy greens in VFs and GHs to be quite similar on an annualized basis (Eaves and Eaves, 2018). Given the greater heat-exclusion (summer)/heat-retention (winter) potential of insulated warehouses, optimizing plant factory artificial lighting (PFAL) may have the greatest potential for CEA energy savings in the long run.

10.3 Pre-LED era

In the late 1940s, fluorescent lamps were mostly used as the source of lighting for photobiology purposes, as they are more energetically efficient than incandescent lights and contain more than 10% blue wavelength of the total photon emission within the photosynthetically active radiation spectrum (PAR, 400–700 nm) (Banis et al., 2018). Fluorescent lighting is not energetically efficient enough to support highly productive plant growth. Also, close positioning to plants could cause serious thermal-scorching issues near electrode ends (Dutta Gupta and Jatothu, 2013). In the 1990s, multitiered PFs in Japan relied upon traditional fluorescent lighting of leafy crops (Kozai, 2013). Fluorescent lighting, especially in combination with incandescent lighting (Biran and Kofranek, 1976), supports vegetative plant growth very well in terms of normal growth habit, coloration, appearance, and product quality similar to what occurs under outdoor or greenhouse solar radiation. However, in terms of growth rate and biomass accumulation over time, fluorescent output intensity typically is limiting. Furthermore, fluorescent lamps decline gradually but steadily in photon output with time of use, and outputs from incandescent lamps decline rapidly. In the late 1970s, high-intensity-discharge (high-pressure sodium and metal halide) lamps made it possible for a fixed spectral-output source of light to grow plants productively (Pattison et al., 2018). The first large-scale commercial indoor farm in the USA was Phytofarm of America, which used high-intensity discharge (HID) lighting of hydroponic vegetables and herbs (Field, 1988). The high thermal-radiation output from HID lamps was absorbed by a recirculating water barrier for each lamp. Without such thermal barriers, HID radiation would scorch leafy greens at the close separation distances required in confined indoor growing spaces and would impose a tremendous thermal-management burden within an insulated warehouse. The high total radiation output from those HID lamps contributed to a substantial electrical-energy cost for the Phytofarm lamps, in spite of scheduling photoperiods to coincide with off-peak power rates.

10.4 Enter light-emitting diodes (LEDs)

LEDs are a solid-state form of light production based upon electroluminescence technology that has multiple attributes conducive to sole-source electric lighting (Morrow, 2008). LEDs operate at low-voltage direct current, are durable, do not require bulky ballasts like HID lamps do, employ heat-sinking remote from photon-emitting surfaces that allows close placement of photon-emitting diode surfaces to plant surfaces, and are waveband selectable depending on the chemical composition of semiconductor materials used to construct the diodes (Bourget, 2008). LEDs have a significantly longer lifespan compared to other sources of lighting. Yeh and Chung (2009) suggested 100,000 h for

LEDs and 1000 and 8000 h for incandescent and fluorescent, respectively, although Bourget (2008) considered 50,000 as the lifespan metric based on the time for LEDs to degrade to 70% of their initial 100% output. Even though the capital cost of early-generation LED fixtures was quite high, LEDs have become the mainstream choice of lighting system for indoor agriculture in virtually all startup indoor-agriculture enterprises in the United States, and this trend is spreading rapidly throughout the PF world. Even as ongoing academic research systematically defines the dynamic, multifaceted light requirements (intensity, spectrum, photoperiod, daily light integral) of different crop species at all phases of their production cycles, growers, entrepreneurs, and investors do not typically wait for this objective information to become mainstream, but invest in current LED technology based upon manufacturer light recipes, claims of fixture performance, and above all, cost. Entrepreneurial drive to establish market share and name recognition often trump prudent business practices. As a result, several generations of LED arrays are available on the market simultaneously. Expensive first-generation, fixed-output arrays including two monochromatic wavebands, typically passively heat-sinked, are giving way to cheaper arrays combining monochromatic and broadband LEDs. The truth is that plants grow under all of these LED arrays, perhaps not always optimally, but more or less pretty well. Some cultivars grow more or faster under some arrays than under others, but they all grow well enough to create marketable, if not profitable, crops. Whether long-term commercial profitability is supported by a given type of LED array for a particular species or cultivar remains to be determined by economies of scale and the test of time. With that background, let's examine first the history of LED use for plant growth and development and then what role the different wavebands or colors of light from LEDs play in those essential plant processes.

10.5 History of LED use for plant lighting

LEDs were invented in 1962, but weren't powerful enough to be used for sole-source plant-growth lighting until the 1980s (Bourget, 2008). Prior to initial LED/plant studies, McCree (1972) published his relative quantum-efficiency (RQE) curve for photosynthesis of multiple plant species showing that, at leaf level and limiting photosynthetic photon flux densities (PPFDs), the broad-band red waveband (600–700 nm) had the highest quantum efficiency for photosynthesis, followed by the blue waveband (400–500 nm), and, surprisingly at that time, green (500–600 nm) also showed good photosynthetic efficiency, with some green wavelengths being even more efficient than some blue wavelengths. McCree's RQE information essentially defined the wavelength range of PAR as 400–700 nm and inspired subsequent plant researchers to apply specific narrow-spectrum wavebands within the PAR spectrum to plants in controlled proportions that only LEDs could provide selectively and with adequate intensity. McCree's study was limited to low light levels and single leaf responses, whereas whole-plant photosynthesis and higher PPFD are desired for more relevant PFAL results.

10.6 First LED/plant-growth tests

Considering all mentioned lighting-source limitations, research in photobiology investigated another lighting source to be at least as efficient as previous electrical lighting sources while possibly having other advantages such as a cool-emitting surface, flexibility in shape and size, easy disposal, longer lifespan, etc. NASA life-science programs sponsored the first plant research with LEDs conducted by a

consortium of academic and industrial investigators in Wisconsin, USA. NASA's interest was to develop a robust, energy-efficient plant-lighting system with low launch mass and volume and with potential for spectral control. The first experiments used red LEDs alone composed of gallium-aluminum arsenide that gave a red emission peak at 660 nm. The red light plus 30 $\mu\text{mol m}^{-2} \text{s}$ of blue fluorescent radiation (because blue LEDs were not yet powerful or efficient enough) gave a total PPFD of 325 $\mu\text{mol m}^{-2} \text{s}$, which caused "Grand Rapids" leaf lettuce to grow equivalent to that under the same PPFD from cool-white fluorescent + incandescent light sources, but at significantly lower input energy (Bula et al., 1991; Hoenecke et al., 1992). Using red radiation alone, seedling hypocotyls and cotyledons became elongated, but simultaneously applying blue radiation at only 15 $\mu\text{mol m}^{-2} \text{s}$ prevented unwanted extension growth (Hoenecke et al., 1992). Those early results not only verified that red radiation drives photosynthesis most efficiently at the whole-plant level, but also that blue radiation has powerful photomorphogenic effects on stem elongation and leaf expansion that go beyond its contribution to photosynthesis per se and contributes to decisions still being made today regarding how much blue light to allocate to LED plant-growth-lighting systems and situations.

10.7 NASA spinoff

NASA subsequently developed several small LED lighting arrays that were flown on the space shuttle to test the growth of food crops for future space bioregenerative life-support systems (Barta et al., 1992; Morrow et al., 1995; Croxdale et al., 1997; Stankovic et al., 2002; Zhou, 2005). Simultaneous ground-based research at the Kennedy Space Center further investigated spectral combinations of LED lighting, including newly available blue and far-red LEDs, on a variety of species in comparison with more traditional plant-lighting systems (Brown et al., 1995; Matsuda et al., 2004; Tennessen et al., 1994; Yanagi et al., 1996). Since the initial studies of LEDs to support plant growth more than 28 years ago, there has been an explosion of research on this topic worldwide, which reflects both the promise of LEDs to advance the science of plant photobiology as well as for energy-efficient plant-growth lighting in commercial PF operations. The ongoing history of LEDs for plant growth is gradually uncovering the roles of different spectral wavebands of light, and is somewhat like rediscovering the value of white light for plant growth and development, wavelength-by-wavelength, also revealing species-by-species and cultivar-by-cultivar variation. This is not particularly surprising, especially since plants evolved under broad-band solar radiation, which varies not only by spectrum and intensity throughout each day, but by duration (photoperiod) and daily light integral (DLI) seasonally throughout the year, as well as by climate and location on Earth, all of which affect the light environment. However, for PFAL, developing "customized prescription lighting" becomes possible in completely controlled environments, which presently is unique to LEDs.

10.8 Sorting out the spectral contributions of LED wavebands

LEDs are more or less "monochromatic," with maximum photon flux density (PFD) for a given waveband occurring at very narrow-spectrum peak absorbance, and with minimal PFD from a spreading-wavelength base on either side of the peak wavelength. At least for the PAR range, each waveband is defined by that low-PPFD, spreading base (typically in 100-nm increments). However, the effectiveness of a given-waveband LED depends to a large extent upon the peak-wavelength output of

that LED (typically 1 nm), where the great majority of photon energy resides. Thus, the efficacy of a given LED to drive or regulate a given plant photo-response typically is defined by its peak energy output and PFD. Although plant physiological processes evolved under broad-band solar radiation and are extremely complex and interactive, using a controlled blend of monochromatic LEDs for sole-source plant-growth lighting allows the grower to manipulate and predictively control plant growth in terms of yield, productivity, and quality. The waveband output of a given LED is determined by the primary composition of diode components, with peak wavelength specificity determined by differential doping of diode alloy composition. Thus, desired plant growth and development outcomes are potentially possible using narrow-spectrum LEDs that may not be possible under broadband sunlight!

10.9 Red light

For many reasons, broadband red light (600–700 nm) is the primary waveband of choice for growing crops indoors, at least for most stages of their cropping cycle, and is the waveband that anchors every LED array used to support plant growth. Of the three major waveband components of the PAR spectrum, red photons have the lowest intrinsic energy content (176 kJ mol^{-1}), yet they are the most energetically efficient of all PAR wavebands in driving photosynthesis (Inada, 1976; McCree, 1972). The combination of red light being the most efficient PAR waveband in the quantum efficiency curve and its relatively low photon energy content sets up red LEDs well to achieve high emission efficacy ($\mu\text{mol photon output/joule electrical energy input}$). The relatively high efficiency of red light in driving photosynthesis may contribute to commercial lighting company marketing claims that red LEDs emit the default waveband of choice to promote vegetative plant growth. This is an oversimplification, of course, since all PAR wavebands contribute to photosynthesis and vegetative growth, but typically at lower efficiency than does red. The red RQE curve for photosynthesis includes more of a broad plateau from 620 to 660 nm than a sharp peak at any specific wavelength within broadband red. Since red LEDs in the range of 620–630 nm initially were cheaper to obtain than at higher peak red wavelengths, early-generation red LED arrays tended to include more lower-range than upper-range red such as 660–680 nm. Thus, early-generation LED arrays had fewer emissions at the photomorphogenic peak of red-light absorption for activation of phytochrome (around 660 nm), which inhibits floral induction of short-day plants under high P_{fr} and of long-day plants under high phytochrome photo-equilibria (P_{fr}/P_{tot}). Next-generation LED arrays including “dark-red” LEDs (peak emission at 660 nm) are more efficient, driving photomorphogenic responses triggered by high P_{fr} . In many ways, the reputation of red LEDs to mostly promote vegetative growth may be more related to P_{fr} inhibition of flowering in some cases than to specific promotion of vegetative growth.

As well as its role in driving photosynthesis per se, red light generally is known to promote fresh and dry weight gain, stem elongation, and leaf expansion for many plant species (Heo et al., 2002; Johkan et al., 2010; Wu et al., 2007). Because the first plant research with sole-source LED lighting was conducted with red LEDs alone, and the test plants grew adequately (Bula et al., 1991; Goins et al., 1998), red LEDs have become the first choice of LEDs to drive photosynthesis and vegetative growth for LED arrays developed for that purpose. In fact, the electrical energy-use efficiency and photon efficacy of LED arrays used for sole-source lighting of lettuce correlates much more strongly with the red-light output of arrays than for any other waveband (Kong et al., 2019). Lettuce growth is particularly responsive to red light.

10.10 Blue light

Broadband blue light (400–500 nm) is on the short-wavelength/high-photon-energy end of the PAR spectrum (260 kJ/mol). Blue is about 25% less efficient than red in the quantum efficiency curve for driving photosynthesis. However, the lower RQE of broad-band blue is offset by engineering advancements in the electrical efficiency and photon efficacy of blue LEDs, with blue being the most efficacious (Nelson and Bugbee, 2014). Plant tolerance for blue light at any given stage of plant development under SSL will be the ultimate determining factor regarding energy cost for the blue component of plant-growth lighting.

Blue light was shown early in the history of plant experimentation with LEDs to be an important component of blended light spectra for plant growth and development. Early-generation blue LEDs weren't efficient enough to include in the first plant-growth LED arrays, so small blue fluorescent lamps were substituted initially to test the efficacy of blue light in plant-growth responses. When it was found that plants growing adequately under red LEDs alone did even better when a small component of blue light was added (Brown et al., 1995; Goins et al., 1997; Hoenecke et al., 1992; Tripathy and Brown, 1995; Yorio et al., 1998), this added momentum to include blue LEDs as they became more efficient. Blue light was found to be important to initiate the synthesis of chlorophyll in some species and promote leaf thickness (Tripathy and Brown, 1995). Even though approximately one-third of the PAR spectrum from midday sunlight consists of the blue waveband (Gomez and Mitchell, 2015), the proportion of blue light that is required, or even tolerated, by plants under SSL conditions tends to be much less than that under natural solar lighting. Total PPFD used to drive plant growth in plant factories typically is kept in the linear, lower-light-limiting range of a photosynthetic light-saturation curve, to avoid wasting light at the saturation level as well as to keep the electric bill for lighting and associated thermal control as low as possible. Total PFAL lighting for leafy greens typically falls within the linear dose–response range of 150–250 $\mu\text{mol m}^{-2} \text{s}$ for photosynthesis, which is an order of magnitude lower PPFD than that for ambient midday outdoor or greenhouse lighting during the growing season. At indoor lighting levels, plants typically are very sensitive to the amount or proportion of blue light in the blended light beam, much more so than in the greenhouse. Blue light plays multiple important roles in photomorphogenic plant development, including stem elongation (Cosgrove and Green, 1981; Dougher and Bugbee, 2001; Kigel and Cosgrove, 1991; Nanya et al., 2012; Okamoto et al., 1997; Shinkle and Jones, 1988) and leaf expansion (Cope and Bugbee, 2013; Dougher and Bugbee, 2001; Johkan et al., 2010; Li and Kubota, 2009), controlled development for both of which is critical to the quality and marketability of leafy salad crops. Too much blue limits plant growth for both parameters (Hoenecke et al., 1992). Blue light also is important for phototropism and stomatal aperture (Blaauw and Blaauw-Jansen, 1970; Folta and Spalding, 2001; Kinoshita et al., 2001; Zeiger, 2010). Also, the chlorophyll content of leaves increases with the proportion of blue in the light source (Hernandez and Kubota, 2016). Use of high-blue SSL to obtain dark-green, thick leaves for a leafy-green lettuce cultivar, then, might come at the expense of leaf area and plant size. If achieving minimum plant size in a given time is important for marketability, then choosing a genetically dark-green cultivar might be a superior choice to using high-blue lighting, unless elevated blue can be applied near the end of the cropping cycle after sufficient leaf expansion already has occurred to quickly bring out the desired degree of greenness. In addition to chlorophyll, blue LEDs have been shown to be required to bring out purple pigmentation related to phenolic and anthocyanin synthesis,

without which traditionally red-leafed lettuces remain green under SSL (Stutte et al., 2009). Contents of carotenoids, lutein, glucosinolates, minerals, and other phytonutrients also are enhanced in tissues of leafy greens, microgreens, and herbs grown under sole-source LED lighting containing a rich component of blue light (Craver et al., 2017; Kopsell et al., 2014).

Blue LEDs, then, are a logical addition to LED arrays, but roles for blue light in commercial PF production are complex, with potentially desirable photo-responses of plants possibly requiring different proportions of blue at different stages of crop development (Cope and Bugbee, 2013). For indoor production of leafy greens, about 5% of low-intensity PPFD as blue is beneficial, but above 10% may become limiting to plant growth (Poulet et al., 2014). Proportions of blue as high as 20% or more may be useful for enhancing pigmentation and phytonutrient content, but the timing of application may be critical. In general, as the B/R ratio of LED lighting increases, plant growth in size decreases (Cope and Bugbee, 2013; Dougher and Bugbee, 2001). However, at 100% blue light, stems actually may grow longer and leaves become more expanded compared to the R/B ratios and white light that has been tested (Hernandez and Kubota, 2016). Such are only some of the reasons being discovered that justify why next-generation LED arrays for research need to have dimmable controls for all wavebands of light in general, but for blue in particular.

10.11 Green light

Broad-band green radiation (500–600 nm) makes up the middle third of the 400–700 nm PAR spectrum. It is medium in photon efficacy (230 kJ/mol) between blue and red. The first plant researchers wanting to test the efficacy of LEDs to support plant growth were limited by the availability of wavebands in the PAR region. Reds were available and improving in efficacy; blues existed but were not efficient enough yet to include in the first arrays; and the same was true for greens to an even greater extent. Because absorption spectra for isolated chlorophylls indicate strong absorption in the red and blue, but almost no absorption in the green, early plant-growth arrays included red LEDs plus supplemental blue light using small blue fluorescent lamps, but next-generation LED arrays included blue LEDs when they became more efficient. However, green LEDs were ignored or overlooked mainly because of misperceptions that green is not important for photosynthesis in intact leaves. However, early plant studies indicated that, even with blue light added to red LEDs, plant biomass accumulation still was better under broad-band fluorescent light (Massa et al., 2008). Something was missing from using just R + B lighting that plants could still use photosynthetically. According to the McCree curve (1972), green light integrated over its entire spectral band actually is not bad at driving leaf photosynthesis, being not much less efficient than broad-band blue light. In fact, some wavelengths within the green band actually have higher quantum efficiency for photosynthesis than a few wavelengths within the blue band. One of the first roles established for green light was to make plants growing under red + blue LEDs easier to inspect visually. Leaves appear purple or gray under such narrow-spectrum RB lighting, and it is very difficult to visually diagnose stress or disease disorders under such narrow-spectrum lighting (Massa et al., 2008). Researchers at the NASA Kennedy Space Center subsequently investigated possible involvement of green light in driving photosynthesis and in regulating plant growth. Six percent green light added to R + B LED light caused lettuce to appear normal but had no significant effect on growth or photosynthesis (Kim et al., 2004a). RGB essentially is perceived by humans as white light, and plants appeared normal with only 6% green in it!

Subsequent studies using 24% green light indicated an increase in plant biomass and productivity compared to other light sources tested (Kim et al., 2004b). Studies applying more than 24% green light, including 50% and 100% green, however, actually reduced plant growth compared to 24% green (Kim et al., 2006). The prevailing interpretation of that body of work is that, for multilayered leafy crops, and/or after leaf canopies close to overhead lighting, red and blue light are strongly absorbed by upper leaf layers, while green penetrates deeply into foliar canopies before being absorbed, and where it ultimately drives photosynthesis. Thus, on a whole-plant or cropping scale, a green component of plant-growth lighting can enhance overall photosynthetic productivity, even though it comes in third on the PAR scale of relative quantum efficiency.

Green light also has effects on plants other than driving photosynthesis per se, especially photosynthesis of shaded leaves. Its presence in ambient light opposes that of blue in that green induces stomatal-aperture reduction and leaf conductance, while blue enhances both of those (Kim et al., 2006; Folta and Maruhnich, 2007). Also, green light opposes the effect of blue to reduce stem and petiole elongation (Zhang et al., 2011). Green light effectively induces shade-avoidance elongation symptoms in plants, much like far-red light does. Obviously, these are not all-or-nothing responses, and net effects on plant growth and development typically are determined by titration of the instantaneous intensity of one waveband against another. Since plants evolved under broad-band solar radiation containing a blend of phyto-active wavebands, more plant responses to green light and its relation to other wavebands undoubtedly remain to be discovered with the advent of discrete LEDs as a plant-research tool. Other than as a research tool, green LEDs are not typically included in commercial LED arrays used for PFAL. That is because the photon efficacy of green LEDs still lags far below that of blue, red, and now even white LEDs (Nelson and Bugbee, 2014). Green radiation that is emitted by commercial LED fixtures typically comes from broad-band-emitting white LEDs.

10.12 Far-red light

The recent availability of improved photon-efficacy far-red LEDs (700–800 nm) opens new opportunities for plant photo-control in PFAL. By itself, only the first few nanometers of the FR waveband are useful in driving photosystem I of photosynthesis (Emerson, 1957), but if FR light is combined with shorter wavelengths in the PAR band, a synergistic stimulation of quantum efficiency occurs involving both photosystems I and II (Zhen et al., 2018). This phenomenon, known as the “Emerson enhancement effect,” suggests that the photosynthetic efficiency of shorter wavelengths can be improved by adding longer wavelengths of light. It also suggests that the best lighting spectra for photosynthesis and biomass accumulation might include FR LEDs in combination with PAR LEDs. Like green light, FR penetrates deeply into closed foliar canopies, where lower leaves are mutually shaded by upper leaves and where the main effects of FR likely are more photomorphogenic than photosynthetic.

In fact, perhaps the first decisions that should be made regarding inclusion of FR in an LED array for PFAL should relate to photomorphogenic and photoperiodic issues, both of which involve the phytochrome pigment system and the powerful role that FR plays shifting the dynamic phytochrome photo-equilibrium (PPE) downward, involving lower P_{fr} . Such choices could be plant-process specific, species specific, or even cultivar specific. Species that are long-day for flowering typically are hastened into reproductive development by the presence of FR radiation together with R light (Deitzer et al., 1979). The reduction in PPE driven by FR can be applied throughout the photoperiod, and can be

achieved as brief end-of-day lighting, or as brief night-interruption lighting (Craig and Runkle, 2012). Why this could be important for growing vegetative greens indoors involves tradeoffs between promoting leaf expansion and preventing premature bolting of quantitative long-day plants before reaching harvest stage. Far-red light also is well known to induce the shade-avoidance syndrome involving internode elongation (Beall et al., 1996). Excessive stem elongation is to be avoided in PFAL. Perhaps the most desirable photomorphogenic effect of FR radiation is that leaves developing in a lighting environment including FR tend to expand more or faster (Li and Kubota, 2009), which can increase plant biomass accumulation through enhanced photosynthetic surface. Far-red-induced reduction in PPE also has been shown to stimulate the accumulation of phytonutrients such as anthocyanins in leaves of leafy greens (Mancinelli et al., 1975), so there are multiple tradeoffs between potentially desirable effects and undesirable side effects of FR. For selective control of crop development within a PF, determining how much FR to apply in a given situation, as well as other wavebands of LED light to include such as green, which is known to counteract the effects of FR as well as blue, remain to be determined for different plant-growth responses.

10.13 White light from LEDs

Which narrow-spectrum LED colors to use for a given plant species or plant response, what intensity and proportion of each waveband to use, and at which stage of crop development to apply such lighting choices, are among the many lighting issues and research questions that must be addressed for PFAL when trying to optimize the lighting environment and save energy and production costs at the same time. In many ways, the use of narrow-spectrum lighting from LEDs for crop production is causing us to rediscover and better appreciate the value of broad-band white light. Because of the bewildering array of choices, complications, interactions, and just not knowing the answers to many of these questions, it has long been asked if white should be the default LED of choice for growing crops in a PF with sole-source lighting (SSL). After all, plants evolved their complex pigmentation and photo-response systems under broad-band solar radiation. However, sunlight itself varies in intensity, duration, and in spectral composition, both diurnally as well as seasonally, and today's crops are genetically and physiologically keyed to respond to such dynamic changes. White (W) LEDs came along after R and B LEDs, but initially were much more inefficient (Bourget, 2008), and so were not widely adopted. They were inefficient because white LEDs actually are blue LEDs with a phosphor coating a surface embedding or surrounding the diode, and absorption of B emissions by the phosphor plus re-radiation at longer wavelengths, with the associated energy loss, is responsible for the lower efficiency (Pimputkar et al., 2009). However, the efficiency of W LEDs improved markedly by the end of the first decade of the 21st century (DoE, 2011), and interest from researchers and growers alike has risen sharply since then. In a study of leaf-lettuce growth comparing the electrical energy-use efficiency of an LED array composed of R + B LEDs versus one composed of cool-white LEDs, the W LEDs expended 32% less energy per unit of dry lettuce biomass accumulated than did the R + B LEDs (Poulet et al., 2014). The availability of additional photomorphogenic and photosynthetic wavelengths in W light clearly has advantages for net photosynthetic productivity.

Phosphors can be varied in composition so that net emissions from white LEDs are perceived as “cool,” “neutral,” or “warm” in tint or color temperature, depending on phosphor composition. However, because white LEDs originate from blue LEDs, none of their emissions are identical

spectrally to those of midday solar light. Nevertheless, plants developing under cool-white LEDs typically are more compact with shorter stems and smaller leaves, whereas plants grown under warm-white LEDs are significantly larger, and those under neutral-whites intermediate in size (Cope and Bugbee, 2013). Plant-growth responses to white tints of LEDs generally follow similar responses to blue light per se, so it is possible to experimentally mimic the effects of different W tints with different blends of dimmable monochromatic R, G, B, and FR LEDs. Recent trends in PFAL LED installation include combinations of primarily W LEDs with varying proportions of supplemental R LEDs, depending on the leafy crop being grown. Because W LEDs emit some G, R, and FR along with B, amounts and proportions dependent upon particular phosphors, and total R dependent on both phosphor and number of supplemental R LEDs rounding out the particular W + R array, varying light prescriptions can be designed to accommodate a range of spectral lighting preferences for particular crops. Another trend is the dumping of large numbers of cheap W LED arrays on the PFAL market. The bad news is that they do not last as long as higher-quality LEDs. The good news is that they are cheap and have been designed to last long enough to make a positive return on investment before failure. This marketing scheme also factors in that the rate of improvement in LEDs for PFAL is occurring rapidly, and promotes the impression that LEDs should be replaced with newer, more efficient versions every few years, anyway.

10.14 UV radiation from LEDs

Solar radiation at Earth's surface includes both ultraviolet (UV)-B (280–320 nm) as well as UV-A (320–400 nm) wavebands that plants have adapted to over time. When grown indoors under SSL lacking a UV component, produce appearance and quality may be different than if grown outdoors. Secondary metabolites and phytonutrients that leafy greens are noted for (Jansen and Bornman, 2012) may be reduced or lacking within plants grown in artificial lighting environments lacking UV radiation, and the question is whether some kind and/or amount of UV is required in PFAL for acceptable product quality. This is a complex issue because of radiation-safety concerns for PF workers, the present high cost and inefficiency of UV LEDs (Nelson and Bugbee, 2014), sparse databases regarding growth and metabolic responses of indoor-grown PF species to UV radiation, and questions regarding possible blue-light substitution for UV in PFAL (Kopsell and Sams, 2013; Stutte, 2009).

Plants growing under low-intensity SSL in the absence of UV radiation often display callus-like intumescence growth (also called edema) on leaves, petioles, and shoot tips (Morrow and Wheeler, 1997). In some cases, an elevated blue component can prevent intumescence formation. In other cases it cannot (Massa et al., 2008). The presence of some FR radiation in the lighting environment also has been shown to prevent intumescence formation, suggesting involvement of the phytochrome system in regulating this complex disorder associated with UV deficiency (Morrow and Tibbitts, 1988). Future breakthroughs in UV LED electrical efficiency and photon efficacy, information from secondary metabolism studies to be conducted with UV and other wavebands, and advancement of technologies to ensure worker safety with UV in the plant-growth environment will determine the future of including UV radiation in PFAL.

10.15 Advances in LEDs for PFAL

LEDs have been a rapidly evolving technology, so it is highly likely that every few years new fixture models with upgraded or different efficiencies and lighting capabilities will become available on the plant-growth-lighting market. Commercial growers will have to consider cost—benefit, breakeven times, lamp performance, and decide whether and when to invest in new LED fixtures for their PFAL enterprise. Commercial LED fixtures may evolve toward sophistication, complexity, and increased cost; or, they may evolve toward simplicity and reduced cost. As research develops “recipes” that optimize lighting conditions (e.g., intensity, spectrum, photoperiod, DLI) for yield, quality, and energy-use efficiency, it is likely that such optima will vary not only from species to species and cultivar to cultivar, but also at different developmental stages within each cropping cycle. Faced with such complexities, the only way growers would be able to implement truly optimum lighting recipes for a given species or cultivar would be to equip with research-grade LED arrays having all the bells and whistles (multichannel wavebands, dimmable, etc.), on a large, commercial scale. Since the expense of doing that is a commercial nonstarter, growers instead will either choose crops that have simple lighting recipes their fixtures can provide, or they will choose compromise lighting conditions that may not be fully optimized but are good enough to get the job done and are profitable enough to keep doing with current LEDs. In that case, the advancement strategy is to incorporate the highest-efficiency LEDs available into arrays and fixtures that can be manufactured as cheaply as possible with a lifespan designed to coincide with the next generation of improved LEDs coming on the market.

10.16 Intrinsic LED efficiency

LED efficiency has been defined both in terms of electrical efficiency as well as photon flux efficacy. Radiated power output divided by electrical power input is the electrical efficiency metric, whereas μmoles of photon output divided by Joules of energy input is the photon efficacy metric. Both definitions are used by LED industry specialists as an index of LED efficiency. Energy-use efficiency, on the other hand, can be defined as biomass of fresh produce yield per unit energy input (g/kWh), and light-use efficiency as biomass of fresh produce per quantum of input energy (g/mol). These definitions are mostly used by plant photobiology researchers. Such efficiency terms have become centers of attention, and studies have been conducted to compare different types of LEDs in those terms. [Massa et al. \(2006\)](#) reported red LEDs to be 21.5% electrically efficient while blue were 11% efficient, whereas cool-white fluorescent were 22% efficient and high-pressure sodium and metal halide were 35% and 29% efficient, respectively. Two years later, [Bourget \(2008\)](#) reported that red LED efficiency had climbed to 25%, followed by blue at 20%, while white LEDs lagged at 10% efficient. Red had become more efficient than metal halide and HPS, but was not as efficient as LPS (27%). White LEDs at that time were less efficient than narrow-band LEDs due to the low efficiency of the phosphor coating of blue LEDs. [Cocetta et al. \(2017\)](#) suggested that LED efficiency increases each decade by a factor of 10, and performance by a factor of 20 based on Haitz’s law. Six years later, blue LED efficiency had risen to the top (49%) followed by cool-white at 33% and then reds at 32% ([Nelson and Bugbee, 2014](#)). Photon flux efficacy was $1.87 \mu\text{mol J}^{-1}$ for blue LEDs with a peak wavelength of 455 nm, 1.72 for reds of 655 nm, and 1.52 for cool whites of 5650 color rendering index. Photon efficacy presently is considered the most useful unit for plant responses to light, including

photosynthesis. The relationship between electrical efficiency and photon efficacy depends on wavelength based on Planck's equation, $E = hc/\lambda$.

Three years later, [Cocetta et al. \(2017\)](#) further characterized the properties of different LED wavebands based on upgrades in electrical efficiency and photon flux efficacy. HPS at $1.76 \mu\text{mol J}^{-1}$ and 38% was used as a lighting reference for the pre-LED era.

In terms of electrical efficiency, blue LEDs most recently continue to be on top with an average of 54.85%, and red LEDs come next with an average of 47.62%. White LEDs are in third with 42.5% efficiency. Short-waveband green LEDs (525–530 nm) are only 16.7% efficient, whereas longer-wavelength greens (575.5 nm) are 30.5% efficient.

[Cocetta et al. \(2017\)](#) reported that red LEDs have the highest photon flux efficacy at $2.42 \mu\text{mol J}^{-1}$, followed by blue and white at $2.17 \mu\text{mol J}^{-1}$ and $1.94 \mu\text{mol J}^{-1}$, respectively. Green LEDs have the lowest PFE values at $0.73 \mu\text{mol J}^{-1}$ and $1.46 \mu\text{mol J}^{-1}$ for the shorter and longer wavelengths, respectively.

Red and blue are the most efficient LEDs as a result of superior diode dopings of indium gallium nitride (InGaN) for blue and indium gallium aluminum phosphide (InGaIP) for red. Another significant change is that white spectra derived from blended beams of monochromatic G + R + B LEDs are more electrically efficient than phosphor-converted white LEDs.

Based upon the latest (2019) Osram opto-semiconductor LEDs in horticulture data application sheets, the best blue LEDs are electrically most efficient at 71% followed by red and far-red with efficiencies of 59% each. Far-red LEDs have a photon flux efficacy of $3.50 \mu\text{mol J}^{-1}$ followed by red LEDs with an efficacy of $3.14 \mu\text{mol J}^{-1}$. Warm-white LEDs have a photon flux efficacy of 2.76 followed by blue and low color-rendering index (CRI) white with efficacies of $2.42 \mu\text{mol J}^{-1}$ and $2.02 \mu\text{mol J}^{-1}$, respectively.

10.17 Advances in LED utilization

As upgrades in LED technology evolve toward improved operating efficiency, PFAL as currently practiced will become more cost effective. However, as efficiency improvements become more incremental, with diminishing returns, cost savings for PFAL also will plateau. Haitz law for exponential increases in LED efficiency and exponential decreases in cost of fixtures over time ([Drennen et al., 2001](#)) already has begun to taper off, especially for narrow-spectrum LEDs. Eventually, diode efficiency per se will plateau, and further sustainability metrics will have to come from advances in sole-source light distribution and optimization of growth environments.

10.18 Distribution of light from LEDs

In isolation, an LED is a point source of radiation that obeys the inverse square law ([Bickford and Dunn, 1972](#)), which explains why radiation from an individual LED declines exponentially with increasing separation distance between the photon-emitting surface (LED chip) and a photon-absorbing surface (leaf). However, the combination of emission angle from LEDs determined by the lens surrounding each chip (typically 120–150 degrees) plus the designed spacing among LEDs on an array together determine the degree of photon-beam overlap designed to provide a coherent beam of light from a given planar fixture to irradiate a given cropping area. The combination of primary optic

lens surrounding each diode plus LED spacing on an array lessens the loss of beam intensity from an array with increasing separation distance compared to isolated, individual LEDs. Fixture beam intensity still declines with distance in a nonlinear fashion, but less than for widely spaced point sources. One cost of overlapping light beams from individual LEDs in an array includes beam spreading beyond the boundaries of the fixture and a drop-off of irradiance at its edges, which causes a certain loss of photons (Cocetta et al., 2017) unless multiple fixtures are then spaced for overlapping array beams over a growth area. That is a common supplemental lighting strategy for large growth areas in greenhouses, but in PFAL with long, narrow shelves on multiple tiers, spillover and reflection of photons into aisles and off of warehouse walls decreases the efficiency of lighting and wastes electricity for SSL. Secondary optics can be fitted over LEDs to reshape beams and reduce such edge effects, but at the cost of LED photon efficacy (Lee et al., 2013). Additional research is required to determine tradeoffs between loss of LED efficiency associated with beam reshaping/collimation versus loss of radiation beyond boundaries of the growth area.

10.19 Leveraging the unique properties of LEDs

Because LEDs are solid-state electro-luminescent devices whose thermal waste is absorbed remotely from their photon-emitting surfaces, the photon beam emitted lacks a significant radiant-heat component (Bourget, 2008). This unique property allows energized LEDs to be positioned close to plant surfaces without scorching them (Massa et al., 2008). This property provides an opportunity to shorten the distance of LED lighting source to plant canopy while more light is transmitted and less energy is expended (Cocetta et al., 2017). This property was first leveraged as “intracanopy” lighting in connection with upright, branching plant-growth habits to overcome mutual leaf shading of overhead lighting (Massa et al., 2005a). Since the light engines in vertical “lightsicles” were continuously dimmable, plants could be grown at the same PPFD as at greater separation distance while applying significantly less electrical power and energy. The relative coolness of LEDs allows such placement so that the intensity—distance limitations of the inverse square law can be avoided. Also, lightsicles were designed so that individual light engines could be energized separately and incrementally to keep pace with growth in height of the crop, thereby irradiating plant surfaces but not empty spaces above the foliar canopy (Massa et al., 2005b). Analogous principles can be employed for overhead, close-canopy, targeted lighting of low-profile leafy-green crops with a laterally spreading, rosette growth habit (Poulet et al., 2014). Much potential remains to develop reliable technology for automated detection of plant position and size during crop production with selective switching of LEDs within an array.

10.20 Phasic co-optimization of LED lighting with the aerial environment

Not all PF crops have the same lighting requirements at all stages of their growth cycle. Investigation of the interaction between spectra, intensity, and time of exposure, including time of day and stage of plant development, is inevitable/necessary (Pattison et al., 2018). Therein lies yet another opportunity to improve efficiency and reduce energy costs for LED PFAL lighting. However, additional research is needed to determine what instantaneous PPFDs as well as DLIs will be appropriate for each species or cultivar that meets minimal crop-lighting needs but does not exceed crop tolerance/saturation at any

given stage of development, as well as to identify what spectrum of PFAL is appropriate for desired growth responses and when. Leaf lettuce has been shown to respond to elevated PPFD and enriched CO₂ only during the first several days of exponential growth, after which optimizing resources can be conserved (Knight and Mitchell, 1988). Also, leaf lettuce is not very responsive to PPFD during the lag phase of young plant development (Poulet et al., 2014).

10.21 Multiple light/growth prescriptions simultaneously in a warehouse

On the grand scale of a PF in a repurposed warehouse, light is the one environmental parameter that can be potentially compartmentalized, with different spectra, intensities, and DLIs on different tiers. With sufficient containment of light beams from overhead fixtures, it should be possible to minimize light pollution across crops and stages of crop development without causing HVAC compartmentalization problems. If future research indicates the need for separate light/temperature/CO₂ environments across species and/or stages of crop development, it may be necessary to divide total warehouse space into multiple compartments or rooms with different environmental combinations. Rather than move plants from compartment to compartment at different stages of their production cycle, lighting parameters and other environmental variables could be adjusted periodically in each cropping compartment. The complexity and cost of maintaining multiple environments simultaneously in the same warehouse would be the tradeoff in this scenario that accommodates dynamic versus static growth environments.

10.22 Summary

The ultimate attainment of productivity, profitability, and sustainability in plant factories and vertical farms around the world will involve the interaction of many factors involving progressive technology, viable business practices, and smart management. PFAL can play important roles in crop productivity energy savings and in environmental sustainability. It will take coordination of improvements in efficiency of LED technology, maximizing productive distribution of outputs from the technology to avoid waste, and leveraging the technology to co-optimize environments for productive plant growth. PFAL will play a central role in realizing these objectives.

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Physical environmental factors and their properties

11

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11.1 Introduction

In order to provide the optimum environment for plants to grow in a plant factory with artificial lighting (PFAL), it is essential to understand the nature of each of the environmental factors and how to measure and quantify them. This chapter describes the physical and chemical properties of the following environmental factors and their measurement: temperature, humidity, CO₂ concentration, air current speed, and number of air exchanges per hour. In addition, the basic concepts of energy balance, radiation, and heat conduction and convection are described in detail. Furthermore, the concept and use of the psychrometric chart are described to introduce its importance in understanding the environmental control of PFALs. Light, one of the most important environmental factors in the PFAL, is described in Chapters 8, 9, and 10. The response of plant growth and development to these environmental factors is described in Chapter 13.

11.2 Temperature, energy, and heat

Temperature is an indication of the sensible heat energy content of an object or a substance. Many plant physiological processes are affected by plant temperature, which is determined by the transfer of heat between plant tissues and the surrounding environment. Therefore, monitoring and controlling the air temperature is critical for managing plant physiological activity and response. In a PFAL, air temperature is often controlled at a relatively constant level, resulting in constant plant temperature and, therefore, consistent physiological activity.

11.2.1 Energy balance

Any object with a temperature above 0 K (absolute zero) emits thermal radiation, including the plants themselves and their surroundings. Energy received by plants includes absorbed radiant energy from lamps and the absorbed infrared irradiation from surroundings. Energy leaving plants includes energy lost through emitting infrared radiation, heat convection, heat conduction, and heat loss through

evaporation. The heat by conduction and convection from leaves is referred to as sensible heat, and that associated with the evaporation or condensation of water is known as latent heat. Plant leaves have high absorptivity in the photosynthetically active radiation (400–700 nm), but the chemical energy fixed by photosynthesis is negligibly small compared to the total energy budget of the plant. Leaves of most species have low absorption in the near-infrared range (700–1500 nm) because those wavelengths are transmitted through or reflected from the leaf. In contrast, absorption is high (approximately 95%) in the far-infrared waveband (1500–30,000 nm), which can contribute significantly to the thermal energy load on the plant.

11.2.2 Radiation

Radiation in the far-infrared waveband is essentially blackbody radiation emitted by surrounding objects. Objects of higher temperature emit larger quantities of far-infrared radiation than objects at a lower temperature.

The primary sources of radiant energy in PFALs are lamps and reflectors. Traditional lamps for growth chambers and greenhouses, such as high-pressure sodium lamps and metal halide lamps, have surface temperatures of over 100°C and emit large quantities of far-infrared radiation. This radiation is absorbed by plants, causing increased plant temperature regardless of the surrounding air temperature, thereby impeding control over plant physiological activity. In PFALs, this challenge is compounded by the short distance between lamps and plants that is desirable for maximizing space use efficiency and plant productivity. Therefore, it is preferable to use light sources that emit much less far-infrared radiation, such as LEDs (light-emitting diodes; surface temperature: about 30°C) and fluorescent lamps (surface temperature: about 40°C).

11.2.3 Heat conduction and convection

Energy is conducted between a plant and its environment at the molecular level. Energy is transferred by conduction from the leaf cells to the air molecules in contact with the leaf. Conductive heat transfer at the interface between leaf and air is limited without convective movement due to the low thermal conductivity of air. Conductive heat exchange can also occur between plant parts and other solid or liquid media. However, the impact of this conductive heat exchange on the plant's energy budget is small, because plants do not have much physical contact with solid objects or liquid media.

Convective heat transfer occurs when air moves across the plant. Temperature gradients between the leaves and air result in corresponding gradients in air density and pressure, which cause turbulence and the initiation of convection. There are two types of convection: free and forced. Free (natural) convection occurs when the heat transferred from leaves causes the air outside the unstirred layer to warm, expand, and thus to decrease in density. This more buoyant warmer air then moves upward and thereby transfers heat away from the leaf.

Forced convection, caused by wind or fans, is more effective in heat exchange. As air speed increases, more and more heat is dissipated by forced air movement. An air current speed of more than 0.5 m s⁻¹ at the leaf canopy is required to promote gas exchange; however, air current speeds greater than 1.0 m s⁻¹ do not significantly increase gas exchange (Kitaya et al., 2000). Also, higher air current speeds are not recommended due to possible mechanical stress on the plant. Therefore, in PFALs, the air current speed is usually controlled between 0.5 and 1.0 m s⁻¹ using air circulation fans to promote

gas exchange. Further, when lamps are placed close to plants, leaves absorb significant amounts of thermal energy from lamps, which increases leaf temperatures. Air circulation can help mitigate leaf temperatures by facilitating convective heat transfer away from the plants.

Controlling leaf and air temperatures uniformly at every growing shelf is important in a PFAL. If air circulation in a PFAL is insufficient, air temperatures at the upper growing shelves will be warmer than lower shelves, causing the leaves in the upper canopy to also be warmer. By providing air movement in the whole PFAL system, the vertical air and leaf temperature gradients can be minimized, as well as differences within each horizontal canopy.

11.2.4 Latent heat—transpiration

Evaporation of water is a cooling process, caused by water absorbing sensible heat from its surroundings when it changes from liquid to vapor. During plant transpiration, water evaporates at the air–liquid interfaces along the pores in the cell walls of mesophyll, epidermal, and guard cells and then diffuses out of a leaf. Thus, transpiration represents a means of latent heat loss by a leaf. A leaf can also gain latent heat if dew or frost condenses onto it.

When 1 g of free water evaporates at 25°C, 2436 J of energy is transferred between the leaf and the air. The rate of transpiration, and thus the amount of latent heat transferred from a leaf via evaporation, depends on the difference in vapor pressure between the leaf's surface and the air immediately surrounding it. Therefore, latent heat transfer increases as the leaf/air temperature difference increases. During unstressed conditions (adequate water supply and fully open stomata), transpiration increases with increasing leaf temperature. As water evaporates from the leaves, leaf temperature decreases, often below the surrounding air temperature.

11.2.5 Measurement of temperature

Temperature is one of the most critical variables to measure in PFALs. Air temperature, leaf temperature, and even media and nutrient solution temperature can all impact plant physiological activity. Additionally, measuring plant temperature and comparing it to the air temperature can indicate if a plant is stressed. In a PFAL, multiple growing shelves are arranged in close proximity to each other both vertically and horizontally. To achieve the greatest control over air and leaf temperatures, it is ideal to monitor air temperature at several locations, both vertically and horizontally along the growing shelves.

Although measuring temperature is relatively easy and inexpensive, selecting the correct temperature-sensing device is important, regardless of the capability and sophistication of the environmental control system. Selection of temperature sensors should be based on operating temperature range, reliability, sensitivity to temperature change, and long-term stability. Thermistors often are chosen because they fulfill these criteria, are relatively inexpensive, and respond quickly to temperature changes. Thermistors are essentially ceramic resistors that change resistance with changing temperature. They are regularly used for climate control applications and are commonly found in digital thermometers.

The thermocouple is another commonly used device for air temperature measurement. A thermocouple consists of two different metals that are combined to produce a voltage related to their temperature difference. There are several types of thermocouples that contain different metals, wire thickness, and thus different costs and accuracy. The most common type for greenhouses, growth chambers and PFALs is a type T (copper-constantan) welded thermocouple. The primary challenge of

using thermocouples to measure air temperature is that they are sensitive to sources of heat other than the air. Specifically, thermocouples can produce erroneously high temperature readings if exposed to direct radiation from the sun or nearby objects. They can also produce erroneously low temperature readings if condensation forms on the metal wires. Therefore, to increase the accuracy of thermocouple measurements, they should be mounted in an enclosed box with a small fan that blows air from the surroundings over the coupled wires.

11.3 Water vapor

11.3.1 Humidity

Water vapor is the gaseous state of water and humidity is a measure of its content in the air. The amount of atmospheric water vapor can range from nearly zero up to 4% of the total mass of air. Absolute humidity (AH), or humidity ratio, is a measure of the actual water vapor content in the air and is expressed as the ratio of mass of water vapor to the mass of dry air for a specified volume of air. The air can hold more water vapor at higher temperatures than at lower temperatures. Relative humidity (RH) is temperature-dependent and used to express the water vapor content of air based on the maximum amount of water the air can hold for a given temperature and pressure. It is most often expressed as a percentage or ratio of the given water vapor content to the maximum at a given temperature. As an example, if the air temperature decreases with no change in water vapor content (or AH), the maximum water-holding capacity of the air drops, resulting in a higher RH.

Water vapor is produced by evaporation from open water surfaces (lakes, puddles, rivers, and oceans) and evaporation from wet surfaces such as soil and plants. In PFALs, plants are constantly adding water vapor to the air through transpiration, which is the evaporation of water from plant surfaces to the atmosphere. Healthy, actively growing plants can transpire a lot of water, resulting in a rapid increase in the water vapor content and humidity in a semiclosed PFAL. When the air-conditioning system is operating, humidity is kept under control because water vapor condenses on the cooling coils, dropping the moisture content, and thus humidity, of the air. Therefore, one approach to controlling humidity in a PFAL is to alternate the operation of lights to generate heat and cause the air conditioner to run, resulting in simultaneous cooling and dehumidification of the space. Alternatively, stand-alone dehumidifiers can be installed in the PFAL that do not rely on the operation of air conditioners. These units may be used in PFAL applications that require distinct day/night cycles, when turning on the lights for dehumidification would be undesirable. They can also be used to avoid operating lights and air conditioners during peak energy use periods, lowering energy costs.

In a PFAL, the amount of condensation can be significant and recycling the condensation is desirable for conserving water. The safety of this condensed water for irrigation should be confirmed prior to use due to the possibility of contaminants such as heavy metal. If used for irrigation, the condensate should be filtered and treated prior to being delivered to plants.

11.3.2 Vapor pressure deficit

Although RH is commonly used as a measure of air humidity, it provides no direct information about the driving force of transpiration and evaporation. Instead, the vapor pressure deficit (VPD) is a measure of the driving force, meaning that transpiration and evaporation rates are proportional to VPD.

VPD is the difference (deficit) between the amount of moisture in the air and how much moisture the air can hold when it is saturated at the same air temperature and is expressed in units of pressure. The SI unit of VPD is kPa (kilopascal), but kg m^{-3} is still used in some literature. As water vapor content increases, water molecules exert more force on each other, resulting in a higher vapor pressure. Therefore, because air can hold more water vapor at higher temperatures, the maximum water vapor pressure is higher at higher temperatures.

When the VPD is too low, transpiration will be inhibited and can lead to condensation on leaves and surfaces inside the PFAL. On the other hand, when the VPD is high, the plant will draw more water from its roots in an effort to avoid wilting. If the VPD gets too high, plants close stomata and shut down the transpiration altogether in an effort to prevent excessive water loss. In a PFAL, the ideal range for VPD is from 0.8 to 0.95 kPa, with an optimal setting of around 0.85 kPa.

11.3.3 Measurement of humidity

As previously discussed, humidity is the amount of water vapor in the air. RH is the most common measure of water vapor content because it relates water vapor content to the maximum water vapor content the air could hold at saturation. For example, 50% RH indicates that the air has half the water vapor that it could hold if it were completely saturated. As the air temperature rises, more water vapor must be added to the air to maintain the same RH.

The traditional method of measuring humidity is to measure both wet bulb and dry bulb temperatures, and then convert to RH using a psychrometric chart. The dry bulb temperature is commonly measured with a standard thermometer. The wet bulb temperature is determined from a standard thermometer modified with a wetted fabric wick covering the sensor bulb. Sufficient air flow is provided over the wick material so that as water evaporates from the wet wick, the temperature falls and the thermometer reading reflects the wet bulb temperature. Since the wet bulb needs to be wet all the time, this method is not suitable for continuous measurement of humidity.

RH can also be measured directly using a hygrometer. There are many types of hygrometers for direct RH measurement with different degrees of accuracy and at various prices. Modern humidity sensors use electronic devices, which are based on changes in electrical capacitance or resistance to measure humidity differences. Most humidity sensors need calibration every year or two to maintain accuracy. Even with frequent calibration, most humidity sensors have low accuracy under very humid (above 95%) and dry environments (below 10%).

11.4 Moist air properties

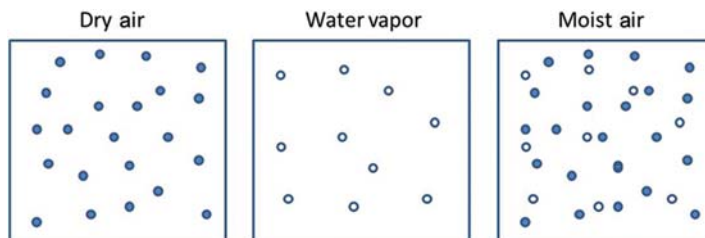
11.4.1 Composition of air

Atmospheric air comprises approximately 78% nitrogen, 21% oxygen, 0.93% argon, 0.04% carbon dioxide (CO_2), a variable amount of water vapor, and other gases. The density of dry air (assuming zero water vapor) under standard pressure (101 kPa) is 1.293 kg m^{-3} at 0°C , 1.205 kg m^{-3} at 20°C , and 1.185 kg m^{-3} at 25°C . Therefore, the higher the temperature, the lighter is the air. Compared with the density of pure water (1000 kg m^{-3}), the density of air is very small.

In reality, air is never completely dry, even in a desert, which means the air is always a mixture of dry air and water vapor (moist air, Fig. 11.1). Although the water vapor content is often less than 1% of

FIGURE 11.1

Schematic diagram of dry and moist air.

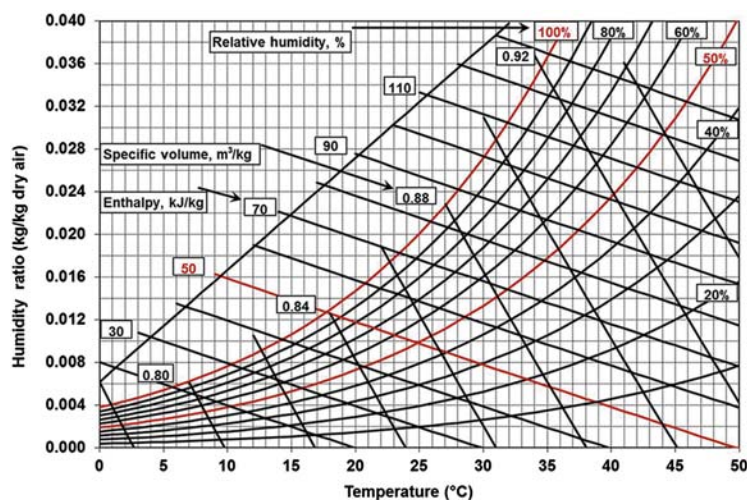


the total, it has a large impact on the condition and overall behavior of air. Water vapor plays a major role in the Earth's water cycle, influences local climate conditions, and both stores and transfers energy in the form of sensible and latent heat. Sensible heat is energy that a person can “feel” and can be measured directly with a thermometer. Latent heat is energy that cannot be felt, and is contained within water until it is transferred to a substance that has less energy.

The process of evaporative cooling demonstrates latent heat transfer. When liquid water evaporates, it absorbs heat from the air around it, causing the sensible air temperature to decrease and the water content (humidity) of air to increase. However, this energy does not disappear. It is “captured” by water vapor in the form of latent heat. Therefore, the energy content of the mixed air does not change, even though the dry bulb temperature has decreased.

11.4.2 Psychrometric chart

Temperature and humidity are often used to characterize the properties of moist air for climate control applications. The psychrometric chart provides a graphical representation of the relationships between water vapor, temperature, and energy (Figs. 11.2 and 11.3). This chart allows all the parameters of

**FIGURE 11.2**

Psychrometric chart. Figure courtesy of Dr. A.J. Both, Rutgers University.

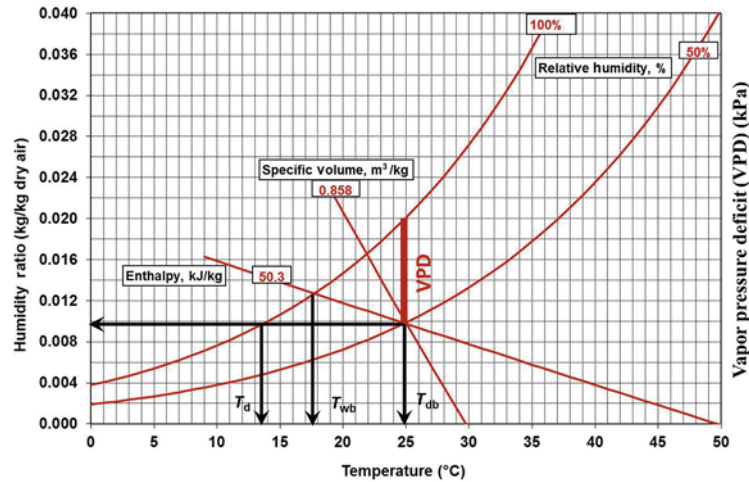


FIGURE 11.3

Simplified psychrometric chart showing dry bulb temperature (T_{db}), wet bulb temperature (T_{wb}), and dewpoint (T_d) of moist air on a psychrometric chart. Figure courtesy of Dr. A.J. Both, Rutgers University.

moist air to be determined when only two of the following independent properties are known: dry bulb temperature (T_{db}), wet bulb temperature (T_{wb}), dewpoint temperature (T_d), AH (also called humidity ratio), RH, and water vapor pressure (P_v). When any two of these six independent variables are known, saturated vapor pressure ($P_{v,sat}$), enthalpy (h), and specific volume (ν) can be determined. By knowing the relationships of these moist air properties, one can predict the effectiveness of various environmental control strategies to influence plant behavior and productivity. Table 11.1 lists the definition and units of psychrometric properties.

Dry bulb temperature, T_{db} , which is commonly referred to simply as “air temperature,” is the air property that is most familiar to people. Dry bulb temperature can be measured using a standard thermometer and indicates the quantity of “sensible heat.” Dry bulb temperature is shown along the horizontal axis of the psychrometric chart. The vertical lines extending upward from this axis represent constant T_{db} (Fig. 11.2).

Wet bulb temperature, T_{wb} , is the temperature of air if it were saturated with water vapor. It is measured with a thermometer that has a bulb covered with a water-moistened wick. The T_{wb} is measured when a constant, known velocity of air is passed over the wet wick. On the chart, the constant wet-bulb lines slope slightly up and to the left. The T_{wb} is read at the saturation line (100% RH). The wet bulb temperature will always be lower than the dry bulb temperature, unless the air is completely saturated with water vapor (100% RH).

Dewpoint temperature, T_d , is the temperature at which the water vapor in air at constant barometric pressure condenses into liquid water at the same rate at which it evaporates. If water vapor comes into contact with solid surfaces that are lower than T_d , liquid water will form into condensation, or dew. Likewise, if the dry bulb air temperature drops below T_d , water vapor will condense within the air itself and produce fog. The dewpoint is associated with RH. A high RH indicates that the dewpoint

Table 11.1 Psychrometric properties related to psychrometric charts and their definition.

Psychrometric property	Unit	Definition
Dry bulb temperature, T_{db}	$^{\circ}\text{C}$	Air temperature measured with a regular thermometer
Wet bulb temperature, T_{wb}	$^{\circ}\text{C}$	The temperature reading from a wetted bulb
Relative humidity, RH	%	The amount of water vapor in the air divided by the amount of water vapor the air can hold at the same temperature and pressure
Dew point temperature, T_d	$^{\circ}\text{C}$	The saturation temperature of the moisture present in the sample of air. It can also be defined as the temperature at which the vapor changes to liquid (condensation)
Absolute humidity, AH	kg kg^{-1} (dry air)	The mass of water vapor per unit mass of dry air (kg kg^{-1}). This quantity is also known as the water vapor density
Specific volume, ν	$\text{m}^3 \text{kg}^{-1}$	The volume of moist air per kg of dry air. Warm air is less dense than cool air, which causes warmed air to rise
Enthalpy, h	kJ kg^{-1}	The total heat (sensible and latent heat) energy per kg of dry air, which increases with increasing temperature and absolute humidity

temperature is close to the current dry bulb air temperature. At RH of 100%, the dry bulb, wet bulb, and dewpoint temperatures are all the same, indicating that the air is maximally saturated with water vapor. When the absolute moisture content remains constant and temperature increases, RH decreases.

Understanding the psychrometric chart can help visualize the properties and behavior of moist air for environmental control of a PFAL or greenhouse. For example, looking at the psychrometric chart, one can see that warm air can hold more water vapor than cold air. Yet, as that air is cooled, the RH increases; and if it is cooled enough, water vapor will condense into liquid when the RH is 100%.

11.5 CO₂ concentration

11.5.1 Nature

CO₂ is a naturally occurring chemical compound. It is a linear covalent molecule and is an acidic oxide, and it reacts with water to give carbonic acid. CO₂ is a nonflammable, colorless, odorless gas at standard temperature and pressure and exists in Earth's atmosphere at this state as a trace gas. As of September 2014, the average atmospheric CO₂ concentration was 395.28 ppm (parts per million) (<http://www.esrl.noaa.gov/>). Atmospheric CO₂ concentration varies with time of day and location depending on absorption and respiration of plants and animals, and human activity. With a molecular weight of 44.01 g mol⁻¹, CO₂ is heavier than air. CO₂ has a melting point of -55.6°C, boiling point (sublimation) of -78.5°C, and gas density (at 1.013 bar and 15°C) of 1.8714 kg/m³. It freezes at -78.5°C to form CO₂ snow. CO₂ is produced from the combustion of coal or hydrocarbons, the fermentation of liquids, and the respiration of humans, animals, and fungi.

11.5.2 Dynamic changes of CO₂ concentration in PFALs

Plants assimilate CO₂ during photosynthesis and release CO₂ during respiration. Small changes in CO₂ concentration can have a significant impact on the rate of photosynthesis of plants. Although essential for plant photosynthesis and growth, CO₂ concentration is probably the least controlled factor in the traditional controlled environment of greenhouses and growth chambers. In a semiclosed PFAL, CO₂ concentration varies not only with “plant activity” (photosynthesis and respiration) but also with human activities. The air exhaled by the typical human is composed of 78.04% nitrogen, 13.6%–16% oxygen, 4%–5.3% CO₂, and 1% argon and other gases (en.wikipedia.org/wiki/breathing). With several people inside a PFAL, the CO₂ concentration can increase to several times higher than atmospheric levels without sufficient ventilation. On the other hand, during the photoperiod, when there is no CO₂ enrichment and no human activity, CO₂ concentration can decrease to a very low level that is close to the CO₂ compensation point, if plants are actively photosynthesizing and the culture room is not actively ventilated. The degree of fluctuation in CO₂ concentration inside the culture room depends on the volume of the culture room (buffering capacity), human occupancy, and plant activity. It is often difficult to detect “CO₂ starvation” because plants grow slowly without any symptoms under low CO₂ concentration. Similarly, a too high CO₂ concentration is equally hard to detect from plant symptoms in most cases. Therefore, to maintain optimal plant growth, it is important to continuously monitor, and preferably control, the CO₂ concentration in PFAL. At minimum, the CO₂ concentration in PFAL should be maintained at or around atmospheric levels.

11.5.3 Measurement of CO₂ concentration

Traditionally, CO₂ concentration is reported in the United States as parts per million (ppm) and in the United Kingdom and Europe as volume per million (vpm or ppmv). The International System of Units (SI) unit for CO₂ concentration is μmol mol⁻¹. Because the absolute values in μmol mol⁻¹ are the same as those for μL L⁻¹ or ppm on a volume basis, there is no need for interconversions. However, it should be noted that CO₂ is often purchased by weight and supplied in pressurized cylinders. The conversion factor from volume to mass (weight) is 1.80 kg m⁻³ at 25°C (note: 1000 L = 1 m³).

Continuous measurement of CO₂ concentrations in PFAL is very important. The most commonly used CO₂ sensor is the nondispersive infrared (NDIR) CO₂ sensor. NDIR sensors are spectroscopic

sensors that detect CO₂ in a gaseous environment. The key components are an infrared source, a light tube, an interface (wavelength) filter, and an infrared detector. The gas is pumped or diffuses into the light tube and the electronics measures how much infrared light is absorbed by the gas pumped into the light tube. Cost for a typical NDIR sensor ranges from US \$100 to \$1000, depending on accuracy. New developments include using microelectromechanical systems to bring down the costs of this sensor and to create smaller devices.

Avoid placing CO₂ sensors in locations where people may breathe directly onto the sensor. Also avoid places close to intake or exhaust ducts, or near windows and doorways, as they may give readings that do not accurately reflect the plant canopy conditions.

11.6 Air current speed

11.6.1 Nature and definition

Air current speed is defined as the distance air travels over a given period of time, such as 1 m s^{-1} . Air velocity is the term used when the direction of air current speed is specified. In this book, air current speed will be used to describe the air movement and air flow in the PFAL growing space.

Insufficient air current speed around plants suppresses gas diffusion in the leaf boundary layer, which subsequently reduces rates of photosynthesis and transpiration and hence plant growth (Kitaya et al., 2000). Maintaining appropriate air current speeds in PFAL creates small turbulent eddies around the leaf surface that facilitate gas exchange between the plants and the surrounding environment, thereby promoting plant growth. Conversely, low air current speeds can cause spatial variations in air temperature, CO₂ concentration, and humidity inside the plant canopy (Kitaya et al., 1998), resulting in inconsistent plant growth. Further, air movement helps to prevent condensation on leaves and other surfaces in the PFAL, helping to prevent unwanted growth of bacteria and molds.

Mechanical fans can be used to generate air movement and control air current speed within the plant canopy in PFAL. They may be strategically located in the PFAL and around shelves to promote consistent gas exchange and uniform plant growth. Without mechanical fans, the PFAL will rely on the natural convection and buoyancy of hotter air to produce air movement around plants. However, these convective air current speeds are extremely low and cannot be controlled. To achieve precise air speed control, special calculations and design strategies regarding the location, number, and capacity of fans are necessary when a PFAL is built.

11.6.2 Measurement

Air current speed is typically measured using an anemometer. When choosing anemometers for use in PFALs, high sensitivity at low air current speeds should be prioritized. Because of the limited space between growing shelves, smaller sizes are preferred.

11.7 Number of air exchanges per hour

11.7.1 Nature and definition

The number of air exchanges per hour (N, h^{-1}) is a measure of how many times the air within a defined space is replaced by new air, which is defined as the ratio of hourly ventilation rate divided by the

volume of room air. For PFALs, ideally N should be small for the purpose of controlling the environment and preventing entry of pathogens and pests. However, a minimum air exchange rate should be maintained to prevent the accumulation of ethylene in PFAL, which can cause damage to the plants. Among the commercial PFALs, N varies largely. For relatively airtight, well-insulated PFALs, the N is approximately $0.01\text{--}0.02\text{ h}^{-1}$ (Kozai, 2013).

11.7.2 Measurement of air exchange

Accurate estimation of the number of air exchanges (N) for a PFAL is important because the photosynthetic rate of plants can be predicted continuously based on N . For greenhouses, various techniques have been used to measure and predict ventilation and leakage rates such as tracer gas techniques, energy balance equations, and measurements of pressure differences between inside and outside (Baptista et al., 1999).

The energy balance method has been used to predict ventilation rates by Kozai et al. (1980) and Fernandez and Bailey (1993). The energy balance method is based on the fact that the ventilation removes energy from the greenhouse as a way of preventing excessively high temperatures. This method requires a large number of variables to be measured; and a single inaccuracy can have a large effect on the final result (Baptista et al., 1999).

The tracer gas technique has a greater accuracy than the energy balance method and uses CO_2 , N_2O , or SF_6 as tracer gases. CO_2 is an inexpensive gas and is commonly used for estimating the air exchange rate of greenhouses and growth chambers. However, when plants are inside the room, CO_2 cannot be used reliably because it will be assimilated by plants. Unfortunately, N_2O and SF_6 are too expensive to be used for large PFALs and for continuous measurement. Water (H_2O) has also been studied as a potential tracer gas. Li et al. (2012) used H_2O as a tracer gas to continuously measure the N of a semiclosed growth chamber based on CO_2 and H_2O balance. When H_2O is used as a tracer gas, the key is to accurately measure the H_2O consumption of the plants and condensation amount, if any. For relatively airtight PFALs with uniform air circulation, condensation occurs at the cooling unit, which can be easily collected and quantified. Gas and liquid flow rates and their balances in the PFAL are described in detail in Chapter 4.

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Photosynthesis and respiration

12

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12.1 Introduction

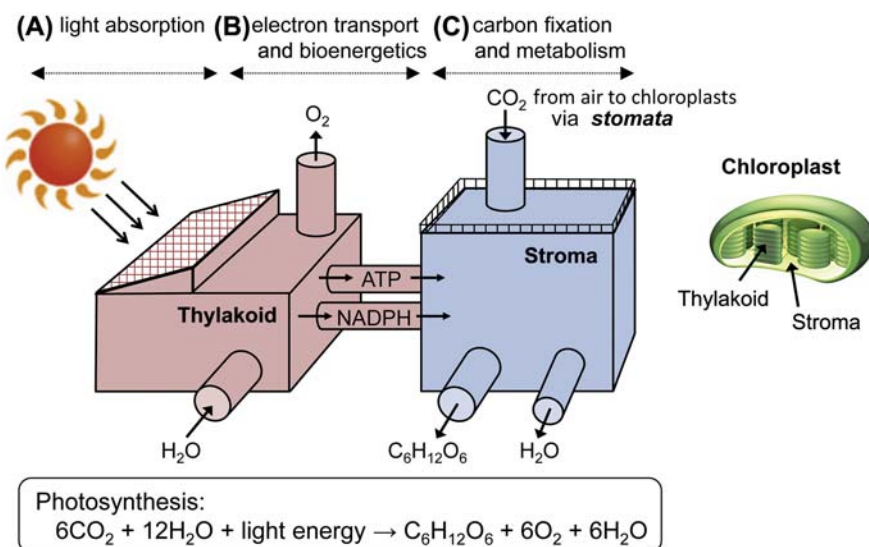
Crop yield is determined by plant growth and more than 90% of crop biomass is derived from the products of photosynthesis. Therefore, photosynthesis is the basic process underlying plant growth and food production. Although respiratory reaction is essentially the opposite of photosynthetic reaction, respiration as well as photosynthesis is also a metabolic pathway that produces chemical energy [i.e., adenosine triphosphate (ATP) and redox equivalents] to meet cell energy demands for growth and maintenance. Thus, plant growth is closely related to both photosynthesis and respiration. There is no growth without photosynthesis and respiration. Therefore, an understanding of the physiological processes of photosynthesis and respiration is necessary for a basic understanding of maximizing crop yield. In addition, plant growth rates are not simply determined by rates of photosynthesis and respiration at the single-leaf level, but are determined by rates of photosynthesis and respiration at the canopy level. In this chapter, the basic reactions of photosynthesis and respiration at the single-leaf level as well as the canopy level are summarized.

12.2 Photosynthesis

Green plants have leaves that contain chloroplasts. The primary processes of photosynthesis occur in the chloroplast in the mesophyll cells of the leaves. Three main processes for photosynthesis can be distinguished: (a) light absorption by photosynthetic pigments, (b) electron transport and bioenergetics, and (c) carbon fixation and metabolism (Fig. 12.1).

12.2.1 Light absorption by photosynthetic pigments

To convert the transient energy of light into stable chemical energy, the photosynthetic apparatus performs a series of energy-transforming reactions in the thylakoid membranes of the chloroplasts (Fig. 12.1). In higher plants, the process is initiated by light capture by an antennae array containing two classes of pigments, chlorophylls and carotenoids, which are responsible for the absorption of light that

**FIGURE 12.1**

Simplified view of photosynthetic reactions in the chloroplasts. Chloroplasts are the site of photosynthesis. Chloroplasts contain membranes arranged in disks referred to as thylakoids, and the region of the chloroplast outside of the thylakoid membranes is referred to as the stroma. The photosynthesis reactions consist of three processes: (A) light absorption by photosynthetic pigments in the thylakoid membranes, (B) electron transport and bioenergetics in the thylakoid membranes, and (C) carbon fixation and metabolism in the stroma.

drives photosynthesis. Chlorophylls are the dominant pigment and strongly absorb red and blue light (Fig. 12.2A). Carotenoids are accessory pigments and absorb blue light strongly, enabling the chloroplast to trap a larger fraction of the light energy (Fig. 12.2A). Isolated chlorophylls and carotenoids transmit green light (Fig. 12.2B). However, it is obvious that intact chloroplasts and whole leaves absorb most of the visible light spectrum, including green light (Fig. 12.2B). Light scattering is an optical phenomenon that influences the global absorption properties of a leaf. Light scattering in leaves is caused primarily by reflection between the intercellular air spaces and cells (Evans et al., 2004). Internal reflection of light increases the path-length, which increases the probability of light capture and absorption. Leaves absorb more than 90% of red and blue light, and also about 70% of green light (Fig. 12.2B). Red and blue light are mostly absorbed in the illuminated side of a leaf due to their high absorption, whereas green light penetrates deeper into the leaf, increasing its chance to be absorbed as it travels a longer path-length with multiple reflections at cell wall/air interfaces (Terashima et al., 2009). An action spectrum, which shows what wavelengths of light are most effective for photosynthesis, clearly indicates that red light is more effective for photosynthesis, but most light within the photosynthetically active region of the spectrum (400–700 nm) is utilized in leaves (Fig. 12.2C).

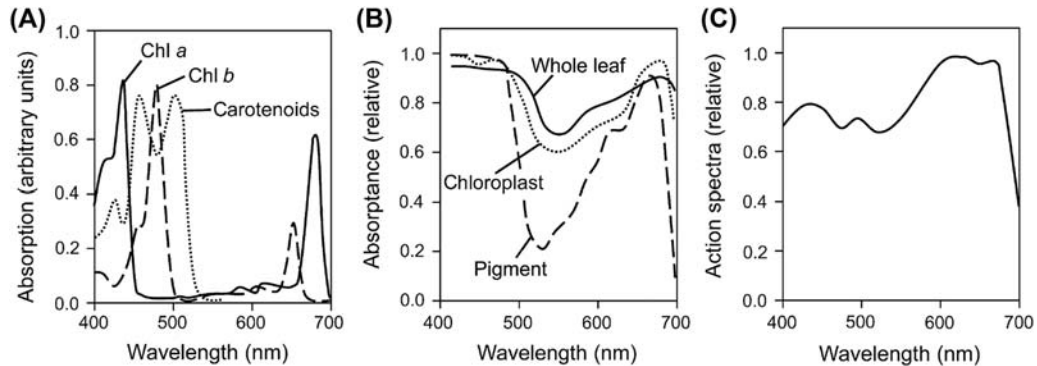


FIGURE 12.2

Absorption spectra of photosynthetic pigments from higher plants (A), absorbance spectra of isolated photosynthetic pigments, intact chloroplasts, and whole leaf (B), and action spectra for photosynthesis (C).

The data are modified from Moss, R.A., Loomis, W.E., 1952. Absorption spectra of leaves. 1. The visible spectrum. Plant Physiol. 27, 370–391, McCree, K.J., 1971/1972. The action spectrum, absorbance, and quantum yield of photosynthesis in crop plants. Agric. Meteorol. 9, 191–216 and Govindjee, 2004. Chlorophyll a fluorescence: a bit of basics and history. In: Papageorgiou, G.C., Govindjee, (Eds.), Chlorophyll a Fluorescence: A Signature of Photosynthesis. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 1–42.

12.2.2 Electron transport and bioenergetics

The energy captured by the photosynthetic pigments is first transferred to the reaction centers of photosystem I and photosystem II in the thylakoid membranes of chloroplasts (Nelson and Yocum, 2006). The electron moves along the electron-transport chain from photosystem II to photosystem I and is finally used for the reduction of NADP^+ to NADPH (nicotinamide adenine dinucleotide phosphate reduced form). The primary electron donor of photosystem II obtains electrons from the hydrolysis of H_2O (water), leading to the production of O_2 (oxygen). During electron transport, an H^+ gradient is formed across the thylakoid membrane, which is used to drive ATP production by ATP synthase. The overall process, which involves both photosystem II and photosystem I, produces ATP and NADPH, which are mainly used for carbon fixation and subsequent carbon metabolism.

12.2.3 Carbon fixation and metabolism

ATP and NADPH are used in the photosynthetic carbon-reduction cycle (i.e., Calvin–Benson cycle, or reductive pentose phosphate pathway) in the chloroplast stroma (Fig. 12.1). In this cycle, CO_2 (carbon dioxide) is assimilated leading to the synthesis of carbohydrates and finally sucrose and/or starch. To fix CO_2 into carbohydrate form, CO_2 needs to be transported from the air to chloroplasts in a leaf. CO_2 in the air diffuses through the stomatal pores in the leaf and then through intercellular airspaces into the cells and ultimately chloroplast as a result of a concentration gradient. Each stomatal pore is

surrounded by a pair of guard cells, and these guard cells can change their turgor and hence aperture in response to various environmental stimuli. The most important variables are light, water status, and CO₂ concentration (i.e., stomata close under low light, water stress, and high CO₂ concentration). Stomatal pores cover only 1% of the total leaf surface, but mainly determine the rate of CO₂ diffusion from the leaf (Evans et al., 2004). Recently, it has been shown that the resistance to CO₂ diffusion from the intercellular airspaces within the leaf through the mesophyll to the chloroplast during photosynthesis is large, and its limitation to photosynthesis is of a similar magnitude as stomatal limitations (Evans et al., 2009). The magnitude of CO₂ diffusion through the mesophyll is considered to be determined by leaf anatomical features such as cell wall thickness and the surface areas of chloroplasts exposed to intercellular air spaces, and by protein-facilitated processes (Evans et al., 2009).

The fixation of CO₂ into carbohydrates is catalyzed by RuBisCO (ribulose 1,5-bisphosphate carboxylase/oxygenase) in the chloroplast stroma. This enzyme makes up almost 50% of the chloroplast protein and is considered to be the most abundant protein on Earth. Through a series of Calvin–Benson cycle reactions, which consume the ATP and NADPH produced in the thylakoid membranes, triose phosphate is produced. Some triose phosphate is transported out of the chloroplast and used in sucrose synthesis, while some remains in the chloroplast and is used in starch synthesis, which is stored in the chloroplast.

Sucrose synthesized within the cytosol of photosynthesizing cells is then available for general distribution and is commonly translocated to other carbon-demanding organs via the phloem (see Section 12.2.3 of Chapter 12). Starch is the principal storage carbohydrate in both photosynthetic and nonphotosynthetic tissues of higher plants (Beck and Ziegler, 1989; Smith et al., 2006). In light, up to 30% of the CO₂ fixed by leaves is incorporated into starch. During the night, starch in chloroplasts is actively degraded and the product of this degradation, sucrose, is exported to the other parts (sinks) of the plant via the phloem (Patrick, 1997). There is substantial variation among plants in the ratio of starch to sucrose during primary partitioning. For example, spinach leaves store significant quantities of sucrose in their vacuoles before starch synthesis begins (Gerhardt et al., 1987), while bean makes starch as soon as photosynthesis exceeds a certain threshold rate (Sharkey et al., 1985). In addition, it should be noted that some plants store other compounds (e.g., sorbitol in the Rosaceae, fructan in asparagus, inulin in artichoke, and so on) instead of starch.

12.3 C₃, C₄, and CAM photosynthesis

In C₃ plants (most vegetables and trees, and several major cereals), CO₂ diffuses through the stomata and the intercellular air spaces, and eventually arrives in the chloroplast. In the chloroplast, CO₂ is fixed by RuBisCO and the first product is a compound with 3-carbon acid, hence, the name C₃ photosynthesis. Triose phosphates are produced through a series of reactions known as the Calvin–Benson cycle, leading to the production of sugars and starch using ATP and NADPH produced by photosynthetic electron transport in the thylakoid membranes.

In contrast, C₄ plants (e.g., some cereals and crops such as maize and sugarcane) have a CO₂-concentrating mechanism that increases CO₂ concentration by 10–100-fold at the catalytic sites of RuBisCO in specialized leaf cells compared to ambient air (Furbank and Hatch, 1987; Jenkins et al., 1989). As a result, the oxygenation reaction of RuBisCO in C₄ plants is greatly suppressed (see Section

12.5 “Photorespiration”). These species are known as C₄ plants because the initial carboxylation reaction produces a 4-carbon acid. A third type of photosynthesis is represented by the so-called CAM (Crassulacean acid metabolism) plants (e.g., pineapple, agave, and ice plant). These plants also possess a CO₂-concentrating mechanism, but it is characterized by a temporal separation of the C₃ and C₄ components, compartmentalized within a common cellular environment (Yamori et al., 2014). The common ice plant (*Mesembryanthemum crystallinum* L.) is known as an inducible (facultative) CAM species, because CAM can be induced in this species by water deficit or salinity stress.

12.4 Respiration

Sucrose and starch are prime sources of respiratory substrates in plants, although other carbohydrates such as fructans and sugar alcohols can also be utilized. Carbon is exported from the chloroplasts to the cytosol and mitochondria, and used to generate redox equivalents (in particular, NADH), ATP and carbon skeletons via glycolysis, mitochondrial tricarboxylic acid cycle (TCA cycle) and mitochondrial electron transport (Fig. 12.3). Generation of these respiratory products leads to CO₂ loss during glycolysis and during reactions in the TCA cycle.

Respiration can be separated into three major components: (1) growth respiration, (2) maintenance respiration, and (3) active uptake of ions by roots. Growth respiration includes the synthesis of new structures in a growing plant and is regarded as proportional to the rate at which new plant material is being formed. Maintenance respiration covers the production of necessary energy for repair and

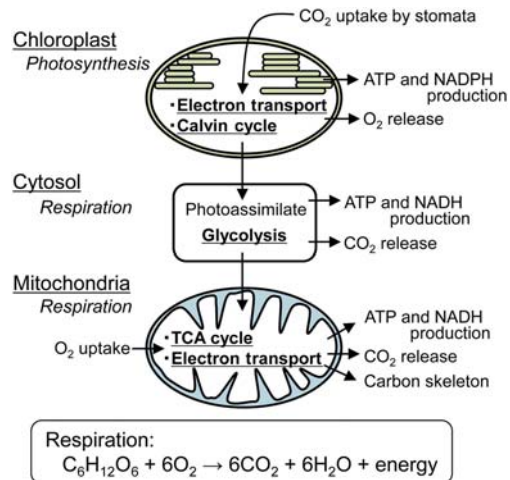


FIGURE 12.3

Simplified scheme involved in photosynthesis in chloroplast, glycolysis in cytosol, and respiration in mitochondria. CO₂ assimilated by the Calvin–Benson cycle and electron transport in the chloroplasts is used to produce photoassimilates (e.g., sugar and starch). The carbon is subsequently exported from chloroplasts to the cytosol and mitochondria, and used to generate ATP, redox equivalents (in particular, NADH), and carbon skeletons (which are necessary for protein synthesis) via glycolysis, TCA (mitochondrial tricarboxylic acid) cycle, and mitochondrial electron transport.

maintenance of the plant. Maintenance respiration includes the energy needed for the turnover of metabolites in a nongrowing plant. Energy needed for maintenance respiration is generally considered to be proportional to tissue mass. It is no longer believed that minimization of respiration would be a feasible way to maximize production of plant organic matter. However, it is important to regulate air temperature in the plant factory with artificial lighting (PFAL), since the maintenance respiration for repair and maintenance of the plant is more stimulated than the growth respiration at high temperature (Rachmilevitch et al., 2006). Energy costs associated with nutrient acquisition by plant roots are often very high because ions have to be transported across root cell membranes using active transport systems that require substantial amounts of ATP. It has been reported that, in young growing plants, respiration for growth and ion uptake together account for about 60% of root respiration, while the maintenance respiration is relatively low (Fig. 12.4). With increasing plant age, the maintenance respiration accounts for an increasing proportion of total respiration (over 85%).

It should be noted that respiration does not directly depend on light, since cells continuously need energy to live. However, in general, the rate of mitochondrial respiration in daytime is 50% or less of that at night, since the light inhibition of respiration seems to be due to the rapid light inactivation of mitochondrial enzymes (Atkin et al., 1998, 2000). Photosynthesis and respiration are metabolic pathways that produce ATP and redox equivalents (e.g., NADPH and NADH) to meet cell energy demands for growth and maintenance. In this way, plant growth is closely related to respiration as well as photosynthesis (Noguchi and Yoshida, 2008).

12.5 Photorespiration

RuBisCO facilitates CO₂ fixation (carboxylation) in the Calvin–Benson cycle, but at the same time, it also fixes O₂ (oxygenation). The latter reaction is the first step of photorespiration. Photorespiration involves the movement of metabolites among chloroplasts, peroxisomes, and mitochondria in a

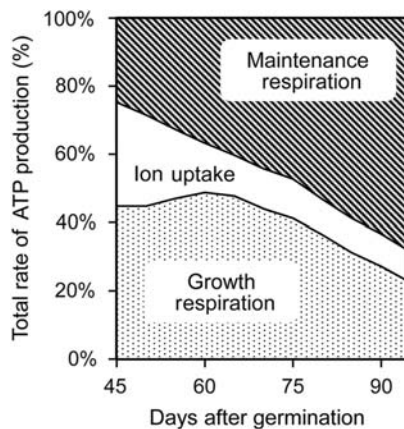


FIGURE 12.4

Time course of the relative contribution of the three major components for root respiration in *Carex* species: (1) growth respiration, (2) maintenance respiration, and (3) active uptake of ions by roots

(modified from Van der Werf et al., 1988)

metabolic pathway that fixes O_2 , releases CO_2 , and consumes ATP. Therefore, it reduces photosynthetic efficiency (Sharkey, 1988). Respiration and photorespiration both release CO_2 in the mitochondria. However, respiratory and photorespiratory processes are well separated with respect to both carbon intermediates and compartmentation.

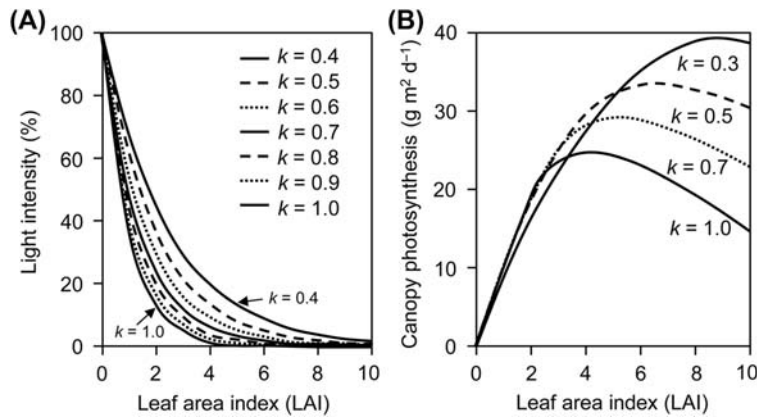
Similar to photosynthesis, photorespiration is a dynamic process, the rate of which can be modulated by light intensity, internal CO_2/O_2 concentrations, or leaf temperature (Jordan and Ogren, 1984). Generally, the photorespiratory rate increases under strong light, high temperature, and low humidity when stomata close and the CO_2 concentration in the leaf decreases. It has been proposed that photorespiration could prevent over-reduction of the chloroplast stroma under conditions of high light and low CO_2 when stomata are closed at midday to prevent water loss (Takahashi and Badger, 2011).

Photorespiration is inherently difficult to measure, although its rate is substantially higher than that of mitochondrial respiration. Net photosynthesis is estimated by the difference between gross photosynthesis and the sum of photorespiration and dark respiration in the mitochondria: net photosynthesis = gross photosynthesis – (photorespiration + dark respiration). The rate of photorespiration is about 25% of the photosynthetic rates in moderate nonstressed conditions, but under stress conditions, it could be 50% or more of the photosynthetic rate. Due to the substantial reductions in photosynthetic efficiency by photorespiration and the fact that increases in CO_2 concentration reduce photorespiration, increasing CO_2 concentration can enhance plant growth both by its effect as a substrate for photosynthesis and by its effect on suppressing photorespiration (Ainsworth and Long, 2005), if other environmental factors are not limiting.

12.6 Leaf area index (LAI) and light penetration

Biomass is ultimately derived from photosynthesis under light. Crop yield commonly depends on the total amount of light intercepted, and the interception of light by a crop canopy is closely related to the total leaf area. The LAI is the ratio of total projected leaf area per unit ground area, and is widely used to characterize canopy light conditions. A canopy with an LAI of 1.0 has a leaf area equal to the soil surface area, but this does not mean that all light is intercepted, since some leaves overlap and there are gaps between leaves in the canopy. Generally, light interception increases sharply with an increase in LAI to about 90% once LAI exceeds 4.0, and approaches an asymptote at a higher LAI (Fig. 12.5A).

Young plants in a crop rarely compete with each other for light irradiation. At this stage, LAI is low (<1.5) and increases in canopy photosynthesis rate are almost proportional to increases in LAI. Thus, new leaf area expansion contributes to the growth rate to the same extent as the existing leaf area, because there are few leaves shading each other. However, in a closed canopy with high LAI (>3.0), leaf area expansion is of minor importance compared with a young crop, because most of the incident radiation is absorbed by the upper leaves of the canopy and thus a further increase of LAI has only a marginal effect on canopy photosynthesis. LAI cannot be too large, because the lower (shaded) leaves would not be sufficiently irradiated and loss of assimilates due to respiration would be higher than gains as a result of photosynthesis (Fig. 12.5B). Values for LAI between 3.0 and 4.0 are typical for horizontal-leaved species; values between 5 and 10 can occur in vertical-leaved species such as cereals and grasses.

**FIGURE 12.5**

Relationship between light intensity within the canopy at a height and LAI from the canopy top (A) and between LAI and canopy photosynthesis (B). k is an extinction coefficient. A canopy with a large k value implies that light intensity decreases rapidly with depth of canopy, whereas a canopy with a small k value would allow light irradiation to penetrate deeply. Canopies with more horizontal leaves have large k values (e.g., tomato, sunflower: 0.7–1.0), whereas canopies with more erect leaves have small k values (e.g., rice, sorghum: 0.3–0.6).

The data in (B) are modified from N  tr, L., Lawlor, D.W., 2005. Photosynthetic plant productivity. In: Pessarakli, M. (Ed.), *Hand Book of Photosynthesis*. second ed. CRC Press, New York, pp. 501–524 and Saeki, T., 1960. Interrelationships between leaf amount, light distribution and total photosynthesis in a plant community. *Bot. Mag.* 73, 55–63.

12.7 Single leaf and canopy

Photosynthesis is the basic process underlying plant growth and food production. It has been clarified that leaf photosynthesis is affected by various environmental conditions such as light (Yamori et al., 2010a), temperature (Yamori et al., 2005, 2006, 2010b), CO_2 concentration (Yamori et al., 2005; Yamori and von Caemmerer, 2009), and so on. However, growth rates are not simply determined by the rate of photosynthesis per unit leaf area of a single leaf, nor by the total leaf area per plant. As light penetrates a crop canopy, it is intercepted by leaves with light intensity declining exponentially with cumulative leaf area (Fig. 12.5A). Canopy photosynthesis can be described as the product of canopy light interception and light use efficiency (Loomis and Connor, 1992). Canopy structure (i.e., LAI and spatial distribution of leaf angles) is important for the canopy light climate and photosynthetic energy conversion. Large leaf angles with leaves close to the vertical ensure good light penetration, leading to a more uniform light environment throughout the canopy. There are positive linear relationships between crop growth rates and canopy light interception for most field crops (e.g., Wells, 1991; Board and Harville, 1993; Heitholt, 1994). Thus, the management of LAI, spatial distribution of leaf angles and environmental conditions are important for improving photosynthetic efficiency. The balance of daytime carbon gain and nighttime carbon loss from the whole plant determines the rate of daily carbon accumulation, which subsequently controls plant growth and development.

In a PFAL, appropriate plant densities are also important for improving the photosynthetic efficiency of crop plants, and consequently yield and quality. Improper plant spacing may cause either too dense or too sparse populations, resulting in a reduction of yield. It is obvious that increasing planting densities would reduce individual weights, leading to reductions in yields. However, the optimum plant density ensures that plants grow uniformly and properly through efficient utilization of moisture, nutrients, and light and thus results in a maximum, high-quality yield.

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Growth, development, transpiration, and translocation as affected by abiotic environmental factors

13

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13.1 Introduction

Understanding of environmental factors affecting various aspects of plant growth and development is crucial in plant factory design and operation. Use of artificial lighting would allow growers to modify one or more selected abiotic environmental factors almost independently, giving opportunities for inducing desired responses of plants (growth, development, flowering, etc.). This chapter first defines vegetative growth (shoots and root growth) and then discusses the typical abiotic environmental factors (temperature, light intensity, light quality, photoperiod, humidity, carbon dioxide concentration, air current speed, and nutrient and root-zone environment) affecting plant growth and development. Then transpiration and translocation of sugar are briefly described using the general physiological understanding of water potential and the sink—source relationship.

13.2 Shoot and root growth

13.2.1 Growth: definition

Plant growth is generally expressed by biomass (fresh or dry mass), which is essentially determined by the cumulative amount of gas exchange (photosynthesis and respiration) over time. Environmental factors affecting plant photosynthesis and respiration are summarized elsewhere in this book. While studies on photosynthesis as affected by environmental factors are often conducted at a single leaf level, quantitatively understanding photosynthesis and growth of the whole plant and canopy is critical in crop production. Leaf expansion and light interception are major determinants of whole plant biomass production, in addition to leaf gas exchange. The relationship between plant growth rate, photosynthesis (assimilation), and leaf area (leafiness) is expressed in the following formula well adopted in plant growth analysis (Hunt, 1982).

$$\text{RGR} = \text{NAR} \times \text{LAR} \quad (13.1)$$

RGR (relative growth rate, $\text{g g}^{-1} \text{d}^{-1}$), NAR (net assimilation rate, $\text{g m}^{-2} \text{d}^{-1}$), and LAR (leaf area ratio, $\text{m}^2 \text{g}^{-1}$) are further expressed with the following equations:

$$\text{RGR} = \frac{1}{W_1} \times \frac{W_2 - W_1}{T_2 - T_1} \quad (13.2)$$

$$\text{NAR} = \frac{1}{L_1} \times \frac{W_2 - W_1}{T_2 - T_1} \quad (13.3)$$

$$\text{LAR} = \frac{L_1}{W_1} \quad (13.4)$$

where W_1 and W_2 are plant dry mass (g per plant) on days T_1 and T_2 , respectively, and L_1 is total leaf area (m^2 per plant) on day T_1 . NAR represents an average rate of leaf photosynthesis of the plant and LAR represents overall leafiness, morphological characteristics affecting light interception, and therefore plant growth rate. Expressing RGR with NAR and LAR is helpful to understand the factors affecting plant growth; however, [Heuvelink and Dorais \(2005\)](#) noted that [Eq. \(13.1\)](#) had some limitations in applying canopy growth with intensive mutual shading, such as a well-established tomato plant canopy. In fact, tomato canopy closure occurs very early in the vegetative stage of the entire production period. In contrast, leafy crops typically grown inside PFALs have low LAI (leaf area index) for a prolonged time before the canopy closure. Therefore, morphological enhancement to promote plant growth may be more effectively used for leafy crops than for tall canopy crops such as tomatoes. A typical growth curve of lettuce plants has been reported by many research groups and it is often a sigmoidal curve showing a rapid biomass increase toward the last third to half of the production period. Therefore, morphological enhancement to increase the light interception during the first half to two-thirds of the crop cycle may largely increase the overall growth (and thereby the yield) of a lettuce crop. Understanding crop species and cultivar-specific growth curves is crucial to obtain maximum productivity in a limited production space.

13.2.2 Root growth

Healthy actively growing roots should be white in color. Roots provide the active surface of water and nutrient uptake. Roots are also sink organs competing for carbohydrate allocation in plants. Root morphology is largely affected by the root zone environment. Plants develop primarily tap roots in root-zone environments with relatively free access to water and nutrients, such as deep flow technique (DFT) and nutrient film technique (NFT) systems, whereas plants develop more finely branched roots with root zones having higher air porosity (and therefore higher oxygen concentration). Adequate balance of root and shoot biomass is desired, but the actual optimum ratio of root and shoot biomass is not well understood, with a few exceptions. For transplants, smaller shoot-to-root ratio (S/R ratio) is generally considered as an important criterion of greater growth capacity and quicker establishment after transplanting. For leafy crops grown in PFALs, no information is available for the optimum root-to-shoot ratios. However, research has been done in greenhouses to quantify the root growth of selected crops grown under different rhizospheric conditions. For example, [Stefanelli et al. \(2012\)](#) demonstrated that increasing nitrogen concentration exponentially decreased the root-to-shoot ratio and linearly increased fresh biomass of lettuce grown hydroponically in a greenhouse. [Nishizawa and Saito \(1998\)](#) showed restricted root and overall growth for tomato plants when root growth was physically restricted in a small container (37 cm^3) compared with those in a large container (2024 or 4818 cm^3).

13.3 Environmental factors affecting plant growth and development

Major and well-studied environmental factors affecting plant growth include (1) temperature, (2) light intensity (daily light integral, DLI), (3) light quality, (4) humidity, or vapor pressure deficit (VPD), (5) CO₂ concentration in the air, (6) air current speed, and (7) nutrient and root-zone environments. Some of the factors are photosynthetic effects and others are morphologic or both. Understanding these key factors is crucial to maximizing the biomass production in plant factories.

13.3.1 Temperature and plant growth and development

Plant growth and development rates are temperature dependent. A typical response curve of plant growth to temperature is shown in Fig. 13.1. Note that the plant growth and developmental rates increase linearly with increasing temperature up to the maximum rate. This relationship is particularly useful to predict these rates under varied temperatures, because as long as temperatures are within the linear range, biomass and developmental stage can be well correlated with the cumulative temperature. In open-field crop production, this concept is called “growing degree days” or “heat unit” and is widely applied in predicting the phenology in crop production. However, outside temperature often exceeds the optimum temperature or may be below the minimum temperature, depending on the weather conditions and seasons. Therefore the growing degree days concept often considers these thresholds (lower and upper thresholds). Considering only the lower threshold (the minimum temperature in Fig. 13.1) is a more common practice than considering both lower and upper thresholds (e.g., AZMET, <http://ag.arizona.edu/azmet>). In contrast, under a controlled environment, especially of PFALs, considering these thresholds is not necessary as temperature is usually maintained within the linear range. This makes the use of cumulative temperature more practical. As an example, when a leafy crop of a selected cultivar reaches harvestable stage 40 days after transplanting when grown under an average temperature of 20.0°C, the cumulative temperature over the growth period is 800° days. Under a different average temperature of 22.0°C, the production time is expected to be 36 days ($36.4 = 800/22$). Average temperature could be adjusted either by altering photoperiod temperature, night period temperature, or both.

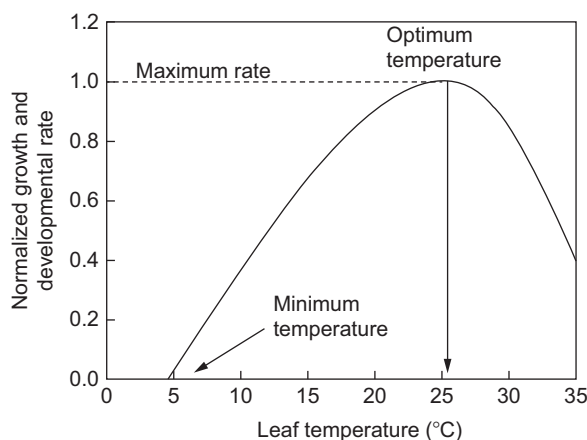


FIGURE 13.1

Plant growth and developmental rate as affected by temperature.

13.3.2 Daily light integral

Under a given temperature condition, the plant growth is further affected by light intensity (irradiance). The response of plant growth to an increase in Photosynthetic photon flux (PPF) is almost linear for many cases under a controlled environment. While high PPF (greater than $1000 \mu\text{mol m}^{-2} \text{s}^{-1}$) typically saturates the leaf net photosynthetic rate (P_n) of C_3 plants, the whole canopy P_n at high LAI is not saturated under the same light intensity that saturates the leaf P_n . Fig. 13.2 shows, as an example, the simulated influence of LAI on the linearity of canopy photosynthetic response over PPF. For this particular case, the canopy photosynthetic response curve became almost linear with LAI = 4.0 or greater. This linearity in photosynthetic light response is in fact the basis of greenhouse growers' perception of "1% increase of light is 1% increase in yield." The linearity in the plant growth rate to daily light integral (DLI, sometimes called daily photosynthetic photon flux) has been observed for lettuce (Albright et al., 2000) grown under a controlled environment. A linear relationship between cumulative yield of tomato and cumulative PAR is also reported by Cockshull et al. (1992). This linear response of plant growth over DLI and the reciprocity between the effects of PPF and photoperiod at the same DLI are useful in lighting design and deciding photoperiod and PPF to obtain target DLI. For example, the target DLI of $12 \text{ mol m}^{-2} \text{d}^{-1}$ can be achieved by $333 \mu\text{mol m}^{-2} \text{s}^{-1}$ for a 10-h photoperiod or $185 \mu\text{mol m}^{-2} \text{s}^{-1}$ for an 18-h photoperiod. A reduction of PPF reduces the number of luminaires and thereby the capital costs, while reduction of the photoperiod could take advantage of the off-peak hours of utility charges.

The minimum DLI is anecdotally recommended for various crops. Generally, target DLI is recommended as $12\text{--}17 \text{ mol m}^{-2} \text{d}^{-1}$ for lettuce and other leafy crops (e.g., Albright et al., 2000) and

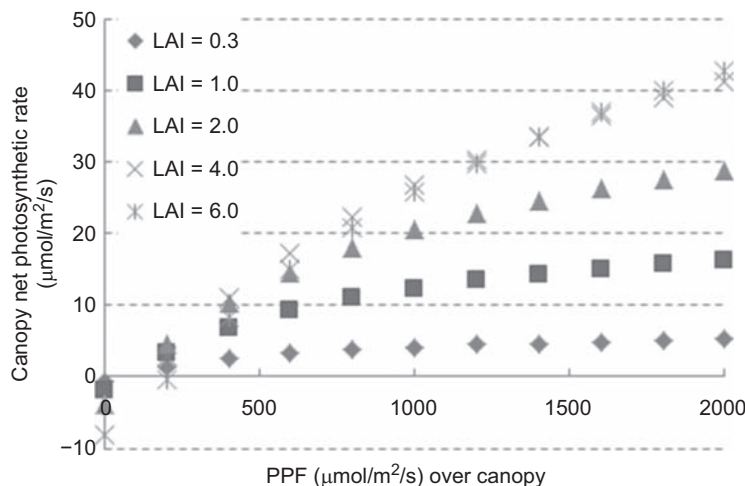


FIGURE 13.2

Canopy net photosynthetic rate as affected by PPF (incident irradiance over the canopy) and canopy leaf area index (LAI). Monsi and Saeki equation (1953) was used for simulating canopy net photosynthetic rate using selected parameters ($P_{\text{max}} = 25$, $k = 0.7$, $R = 2$, $\alpha = 0.07$, where P_{max} is the maximum leaf net photosynthetic rate at saturating PPF; k is the PAR extinction coefficient of the canopy; R is the dark respiration rate; and α is the quantum efficiency).

$13 \text{ mol m}^{-2} \text{ d}^{-1}$ for vegetable seedlings (Fan et al., 2013). The DLI requirement for strawberries is likely to be at a similar level to these crops per our experience at the University of Arizona. Micro-greens do not require high DLI but little data are available. These DLIs are relatively smaller than for tall crops. For example, optimum DLI for high-wire tomato plants is $30\text{--}35 \text{ mol m}^{-2} \text{ d}^{-1}$ (Spaargaren, 2001), more than twice the DLI for leafy crops or seedlings. The DLI requirement in fact determines which crops can practically be grown in energy-intensive PFALs. Further studies are needed to identify the minimum DLI recommended for various species and cultivars grown in PFALs.

13.3.3 Light quality

Although this is currently an intensively studied area, with new information using various LEDs rapidly accumulating, generalization of light quality effects on plant growth seems to be most challenging. This may be because light quality affects both photosynthesis and morphology. The morphological response seems to be largely species and cultivar specific, while photosynthetic responses are generally similar, at least considering the quantum yield (McCree, 1972). As described in an earlier section, quantum yield is the maximum efficiency of photosynthetic photochemical reactions expressed as the yield of the reactions (CO_2 absorption) per photon absorbed. While CO_2 absorption is the result of carboxylation, the quantum yield strictly concerns the efficiency of thylakoid reactions (photosystems), and quantum yield is generally quantified under the conditions where the light is the limiting factor (at light compensation point). Also the terminology changes to quantum efficiency when irradiance (incident light) is used instead of absorbed photons (quantum efficiency = CO_2 exchange rate per photon received over the leaf). The quantum efficiency averaged for 22 plant species (McCree, 1972; Sager et al., 1988) suggests that plants potentially have higher photosynthetic efficiency in red light compared with blue and green light. As PPF increases, light use efficiency of photosynthesis declines as RuBP carboxylation becomes the limiting factor (see more information in Chapter 12). While green light has the lowest quantum yield, green light can penetrate deeper in the plant canopy due to its high transmittance and reflectance. Therefore, theoretically, quantum yield of a dense plant canopy should be more equalized over the 400–700 nm range. In fact, Paradiso et al. (2011) validated this hypothesis using a mathematical simulation considering single leaf response and canopy light penetration for rose plants, demonstrating that canopy quantum efficiency of green light is not that much lower than that of red light, compared with what McCree (1972) and Sager et al. (1988) show for leaf quantum efficiency under green versus red light. This is quite useful information for PFALs as it encourages the scientific community and the horticultural LED R&D to focus more on plant morphological response and energy use efficiency rather than the photosynthetic response to light qualities.

Another critical influence of light quality on plant photosynthesis is through stomatal conductance. Blue light is known to increase stomatal conductance and plants grown under blue-rich light environments exhibit a greater leaf net photosynthetic rate than those grown under spectra limiting blue light (e.g., Bukhov et al., 1995; Hogewoning et al., 2010). However, blue light also has strong morphological influences of reducing light interception (and the overall growth) as described in subsequent sections, and the increase in stomatal conductance often does not result in increased growth.

Many studies have examined the plant photomorphogenic response in the past several years. Plant growth promotion through morphological enhancement (i.e., enlarging leaf area and thereby light interception) is a unique concept and several research groups demonstrated that blue light and far-red light seem to take the major roles. Cucumber plants were grown under varied red to blue photon flux

ratios of sole-source light in PFALs (Hernández and Kubota, unpublished) as well as supplemental light in a greenhouse (Hernández and Kubota, 2014) and it was found that increasing blue light at the same overall PPF decreased the leaf area (LAR) and thereby the growth under relatively low background solar daily light integral ($\text{mol m}^{-2} \text{d}^{-1}$). Supplemental far-red (700–800 nm) lighting also has significant influence on stem elongation as well as leaf expansion. Use of incandescent lamps has been practiced for many years in growth chambers for various plant research (Sager and McFarlane, 1997). Using far-red LEDs, Li and Kubota (2009) and Stutte (2009) demonstrated that supplemental far-red lighting enhanced lettuce leaf area and overall growth. Both reports discuss that the lettuce growth promotion under supplemental far-red lighting was associated with an increase in leaf area and consequently improved light interception. Similar morphological influence of far-red light can be achieved by end-of-day (EOD) far-red application. Chia and Kubota (2010) and Yang et al. (2012) demonstrated that morphology of grafting rootstocks for tomato and cucurbits could be improved significantly by applying EOD far-red lighting using both stationary and movable light fixtures.

13.3.4 Humidity (VPD)

Leaf transpiration rate (discussed further in following sections) is strongly affected by the moisture concentration (or vapor pressure deficit) of surrounding air as well as leaf temperature. Therefore, VPD indirectly affects nutrient uptake, leaf temperature, and thereby plant growth and development. Among mineral nutrition, Ca uptake is strongly affected by mass flow driven by plant transpiration, as described elsewhere. In PFALs, Ca deficiency has been recognized as a critical issue due to suboptimal airflow around the shoot tips (Goto and Takakura, 1992; Frantz et al., 2004). Increasing VPD during the photoperiod or decreasing VPD during the night period is reportedly effective to reduce the tipburn incidence of lettuce plants grown under artificial lighting (Collier and Tibbitts, 1984). VPD management can be an effective tool to control localized Ca deficiency in leafy crops, especially when creating a vertical air flow is not possible within the limited headspace inside the shelf where plants are grown at high density.

13.3.5 CO₂ concentration

CO₂ enrichment is widely practiced in PFALs except in those facilities that have limited capacity of CO₂ control due to the highly ventilated buildings used for production. For example, in North America, use of existing buildings such as warehouses is commonly done for PFALs. According to the building standard for ventilation (ASHRAE, 2013), warehouses require a minimum of $0.3 \text{ L m}^{-2} \text{ s}^{-1}$ air exchange rate and offices require an additional ventilation (2.5 L s^{-1} per person) depending on the occupant density (number of people). For an office building of 3 m wall height, a 100 m^2 floor area that was designed to occupy five people has a minimum ventilation of 37.5 L s^{-1} or 0.45 h^{-1} air exchange, as a requirement. This level of ventilation rate may not economically permit increase of CO₂ concentration to the level higher than ambient because much of the CO₂ injected into the building will be lost due to the ventilation. Ohyama and Kozai (1998) demonstrated that the amount of CO₂ lost to the outside is greater than that absorbed by the plants growing in PFALs when the system has as low as 0.1 h^{-1} ventilation rate. The effect of ventilation rate on the CO₂ budget (plant uptake vs. loss to the atmosphere) is further discussed in Chapters 5 and 11 of this book. For highly vented structures, it is recommended that CO₂ be maintained at near ambient concentration (around 400 ppm) so that there will be no virtual loss of CO₂ to the outside atmosphere (Ohyama et al., 2005).

Plant responses to high CO₂ concentration have been studied intensively in the field of environmental sciences. Generally it is known that plants increase stomatal resistance under elevated CO₂ (Ainsworth and Rogers, 2007), which thereby increases the water use efficiency. The optimum temperature of photosynthesis also becomes higher under high CO₂ concentration due to the lower solubility of CO₂ at higher temperature and lower specificity of RuBisCo for CO₂, resulting in a greater effect of elevated CO₂ at higher temperatures (Long, 1991). The actual horticultural impact of CO₂ enrichment seems to be species specific as well as growth-stage specific. Kimball (1986) summarized the reported impact of CO₂ enrichment in greenhouses, where there was a notable trend that plants in the vegetative stage more pronouncedly responded to the high CO₂ concentration than did those in the reproductive stage. For example, average yield increase in tomato under CO₂ enrichment reported by 131 articles was 17%, whereas the average increase in vegetative biomass of immature crops was 52% (average of values reported by 24 articles). Similarly, CO₂ enrichment increased head lettuce marketable yield and vegetative biomass of immature crops by an average of 35% and 68%, respectively.

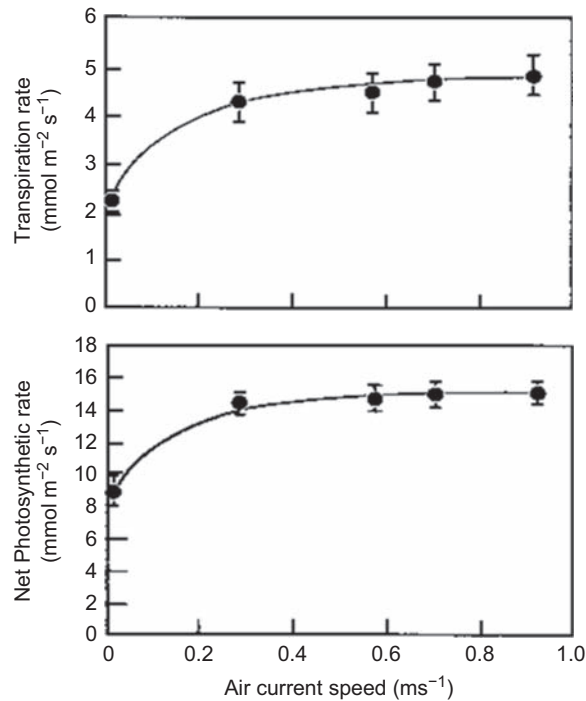
13.3.6 Air current speed

Air circulation inside a plant production system is often considered for achieving better spatial uniformity of air temperature. When air circulation fans are applied, we must avoid strong air current speed around the plants that may cause mechanical stress and damage. Wind-induced shaking and the resulting mechanical stress on plants reportedly reduce internode length as well as leaf size (e.g., Biddington and Dearman, 1985). These plant responses are often observed at air current speeds greater than 1 m s⁻¹. The influence of much slower air current speed has also been studied and there are often positive influences enhancing photosynthetic or transpirational gas exchanges of leaves by reducing the boundary layer resistance. Fig. 13.3 (Kitaya et al., 2000) shows the enhanced transpiration rate and net photosynthetic rate of sweet potato leaves measured under different air current speeds.

As described in Chapter 15 on tipburn in this book, one application of this enhanced gas exchange by increasing air current speed is the prevention of tipburn in lettuce-growing greenhouses by using vertical air flow fans (Cornell Univ. Lettuce Handbook), following the well-designed studies conducted to show the proof-of-concept (Goto and Takakura, 1992). Goto and Takakura (1992) showed that localized air circulation around the shoot tip enhanced the calcium concentration of the tissue and dramatically reduced the incidence of tipburn. When applied in greenhouses, the vertical fans can be distributed to obtain a 0.5 m s⁻¹ average downward air current speed over the canopy, computed from fan capacity (m³ s⁻¹) and density (m⁻²) (L. Albright, personal communication). As mentioned earlier, applying this practice in PFALs is challenging due to the limited headspace for installing vertical airflow fans in typical vertical growing systems. Air current speed also affects the leaf energy budget and enhances the sensible and latent heat transfer between leaf and the surrounding air.

13.3.7 Nutrient and root zone

As discussed elsewhere in this book, plants respond to various chemical and physical properties and variables in their root zone. In fact, the interactions between these factors are complex and much research is needed to optimize the root zone environment. Major factors that we use as controlled variables are EC (electrical conductivity), pH, and DO (dissolved oxygen concentration) in PFALs as well as in greenhouse hydroponics. Keeping all factors within optimum ranges is critical in plant production. When deep flow hydroponic systems are used, plant roots are submerged in the nutrient solution and therefore maintaining a high DO is recommended. Zeroni et al. (1983) demonstrated the reduction of tomato

**FIGURE 13.3**

Effect of air current speed on the transpiration rate and net photosynthetic rates of a single leaf sweet potato (Kitaya et al., 2000).

yields with lowering DO in a deep-flow hydroponic system. The design of nutrient delivery in hydroponic systems also affects the DO in the solution circulated within the system. For example, NFT systems employ different slopes to assure circulation of the nutrient solution and prevent depletion of DO in the solution. López-Pozos et al. (2011) showed that having steeper slope (4%) and gaps within the slope improved the DO in the solution and increased tomato yield grown in the NFT system.

In hydroponics, grower practices include weekly nutrient analysis to assure no critical accumulation or depletion of specific elements in the nutrient solution and adjusting the fertilizer concentration accordingly. However, because of the complexity of multiple factor interactions, optimization has not been done fully and often both researchers and commercial practitioners compromise with available fertilizer recipes and management practices. Further information can be found in chapter 14.

13.4 Development (photoperiodism and temperature affecting flower development)

Plant flowering is generally affected by photoperiod and temperature. In general, photoperiodic flowering responses are classified into the following five types:

- Obligate short day
- Facultative short day

- Day neutral
- Obligate long day
- Facultative long day

Short-day plants develop flowers when day length becomes shorter (or night length becomes longer). When the critical (threshold) length clearly distinguishes the plant's responses between longer and shorter day lengths, the photoperiodic response is classified as *obligate* type. *Facultative* response is quantitative where flowering responses are promoted by certain photoperiods (Runkle and Fisher, 2004; Erwin et al., 2004). Day-neutral plants are insensitive to photoperiod. Because photoperiod is not the only factor affecting flowering responses, classification of photoperiodic flowering responses must be done in carefully designed experiments excluding interactions with other factors (such as temperature). Ideally, photoperiod should be varied by applying different durations of artificial lighting at minimum irradiance inducing the photoperiodic response so that differences between different light treatments are not largely due to DLI. Photon flux of $2 \mu\text{mol m}^{-2} \text{s}^{-1}$ seems to be adequate (e.g., Heins et al., 1997) and the photoperiod extension light should contain both red and far-red light (Craig and Runkle, 2013).

For floriculture and ornamental crops, regulation of photoperiodic response is crucial and, for that reason, foundational knowledge of species-specific photoperiod and temperature requirements for flowering is now available at least for the major ornamental species. For example, use of night interruption lighting to promote flowering of long-day plants (such as *campanula*) or to prevent flowering of short-day plants (such as *chrysanthemum*) is widely practiced. Further, a more detailed classification of photoperiodic response as either facultative or obligate has been applied to many floriculture and ornamental species (Erwin et al., 2004). In contrast, limited information is available for food crop species. For tomato, there is conflicting information on its photoperiodic response. Generally it seems that tomato is believed to be day neutral, but some cultivars are regarded as quantitative short-day plants (Heuvelink, 2005; Hurd, 1973). In North America, many strawberry cultivars are classified into “day neutral” without precisely identifying their “insensitiveness” to photoperiods. Bradford et al. (2010) challenged the traditional classification and found that the classification required correction for some of the cultivars examined. Lack of information of specific photoperiodic responses is particularly the case for crop species grown in open fields where photoperiod is an uncontrollable factor specific to the geographical location and season.

In addition to photoperiod, flower development of many species is affected by temperature. There are often interactions observed between the effects of temperature and photoperiod. Table 13.1 shows the example of Japanese strawberry flowering responses. This foundational knowledge was developed to meet the need of off-season production of strawberry. This type of information will be needed for various flowering crops as PFALs have the capacity of controlling environments precisely to induce flowers at an ideal timing relative to the scheduled timing of harvesting.

13.5 Transpiration

Transpiration refers to evaporation from plant tissue. The process is quite passive, driven by the water vapor difference between the stomatal cavity (or intercellular space) and the surrounding air. When stomata are open, almost all transpiration occurs through the stomata, but plants also transpire through the cuticular layer, which is referred to as cuticular transpiration. Cuticular transpiration dominates in darkness as plants close stomata. As gas diffusion, the transpiration rate is affected by the water vapor concentration in the surrounding air, leaf temperature, as well as the boundary layer and stomatal

Table 13.1 Typical interactions of temperature and photoperiod for flowering of strawberry (determined for Japanese cultivars) (after Saga prefecture “Strawberry cultivation manual”).

Type	Average temperature			
	<5°C	5–12°C	12–26°C	>26°C
June-bearing	No flower induction (dormancy)	Flower induction under all photoperiods	Short day (8–13 h) promotes flower induction	No flower induction (critical temperature depends on cultivars)
	<5°C	5–15°C	15–30°C	>30°C
Ever-bearing	No flower induction (dormancy)	Flower induction under all photoperiods	Flower induction under all photoperiods, but number of flowers increases under longer day (facultative response)	Flower induction is suppressed

resistances. The water diffusion process in transpiration is described using the following equation, similar to stomatal CO₂ diffusion in photosynthesis:

$$E = \frac{V_{\text{in}} - V_{\text{air}}}{R_s + R_b} \quad (13.5)$$

where E is the leaf transpiration rate ($\text{mol m}^{-2} \text{s}^{-1}$) through the system having water vapor concentrations in the stomatal cavity (V_{in} , mol m^{-3}) and surrounding air (V_{air} , mol m^{-3}) and stomatal and boundary layer resistances (R_s and R_b , s m^{-1}). From this equation, it is clear that increasing resistances either by closing stomata or creating a thicker boundary layer (by limiting air circulation) would reduce the leaf transpiration rate. V_{in} is usually considered to be close to saturated water vapor concentration at leaf temperature, and therefore increasing leaf temperature (by increasing shortwave radiation) would increase the transpiration rate. Lower V_{air} also contributes to increasing transpiration rate.

Another important understanding of water flux in plants is the hydraulic continuum through the root zone, roots, stems, leaves, and finally surrounding air. Quantifying water potential in such a continuum is helpful to understand water flux and its driving force. Water flux occurs following the water potential gradient (from less negative to more negative). Water potential (Ψ , Pa) is defined in terms of the chemical potential of water (μ_w , J mol^{-1}) and expressed using the following equation:

$$\Psi = \frac{\mu_w - \mu_{w0}}{V_w} \quad (13.6)$$

where μ_{w0} is the chemical potential of water at a reference state consisting of pure water at the same temperature and atmospheric pressure. V_w is the partial molar volume of water ($\text{m}^3 \text{mol}^{-1}$). Therefore Ψ equals zero for pure water. When water content becomes less in a given system (such as plant tissue), Ψ becomes more negative. Furthermore, water potential in plants can be expressed with multiple components.

Table 13.2 Typical values that may be seen in the root zone—plant—air system.

Location	Water potential (Ψ , MPa)
Hydroponic nutrient solution	−0.08 ^a
Soil, 0.1 m below ground and 10 mm from root	−0.3
Plant tissue (xylem of roots and leaves)	−0.8 to −0.6
Air inside the stomatal cavity (95% RH)	−6.9
Air just outside stomata (60% RH)	−70.0
Air just outside boundary layer (50% RH)	−93.6

^aValue reported by [Fujiwara and Kozai \(1995\)](#).
 Adopted from [Hannan, J.J., 1998. Greenhouses. Advanced Technology for Protected Horticulture. CRC Press, Boca Raton, FL, USA](#)
 and [Nobel, P.S., 1991. Physicochemical and Environmental Plant Physiology. Academic Press, New York.](#)

$$\Psi = \Psi_p + \Psi_o + \Psi_m \quad (13.7)$$

where Ψ_p , Ψ_o , and Ψ_m are the components associated with the pressure, osmosis, and matric pressure. The water potential of moist air can also be found using the following equation using its relative humidity (RH, %):

$$\psi = \frac{R \cdot T}{V_w} \cdot \ln \frac{RH}{100} \quad (13.8)$$

where R is the gas constant ($8.31 \text{ J mol}^{-1} \text{ K}^{-1}$) and T is the air temperature in Kelvin (K). [Table 13.2](#) has some typical values of water potentials ([Hannan, 1998](#)). The difference in water potential is the largest between the air inside the stomatal cavity and the air surrounding the leaf, indicating that this is the driving force inducing the water flow in the plants. When stomata are closed at night, the difference in water potential between the root zone and the root tissue allows continuous water flux, maximizing the turgor pressure of the plants. Excessive transpiration (due to dry air or more negative water potential of the air) could induce more negative water flux enough to lose turgor (wilting).

13.6 Translocation

Translocation is driven by pressure flow induced by the difference in water potential between sink and source regions of phloem. Sugars synthesized in source tissues (i.e., leaves) are loaded into the sieve elements of the leaves, increasing turgor pressure of the sieve elements due to the simultaneous water flux from the xylem to the phloem. In contrast, unloading sugars into the sink tissue from the phloem increases the water potential, allowing water flux to the xylem and reducing turgor. Both loading and

unloading could involve symplastic or apoplastic pathways. Apoplastic import of sugars is through the plasma membrane of the cell or the tonoplast of the vacuole in the cell, and therefore requires metabolic energy. [Kitano et al. \(1998\)](#) demonstrated that localized heating around tomato fruit (sink organ) enhanced sugar translocation.

Understanding translocation and the sink–source relationship is especially critical for fruiting crops such as tomato and strawberry. Sugars accumulated in leaves are known to induce negative feedback of photosynthesis by reducing hexokinase as well as RuBisCo activity, and promoting translocation of sugars from leaves to fruits can prevent this feedback inhibition. Promoting translocation of sugars is also important for leafy crops to maximize the whole-plant photosynthetic rate. The sink–source relationship is well studied for tomato (e.g., [Ho, 1988](#)) whose assimilate availability (source strength) is lower than assimilate demand (sink strength), demonstrated by increased fruit size when fruit pruning is applied ([Heuvelink and Dorais, 2005](#)). The sink–source relationship may be a vague concept as it is difficult to quantify the actual strength; however, understanding the balance of sink and source is important to develop cultural practices such as pruning leaves and fruits to optimize the balance, maximizing crop productivity.

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Nutrition and nutrient uptake in soilless culture systems

14

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14.1 Introduction

Although various systems are used in soilless culture and an original nutrient solution suitable for each system is often proposed, the basic principles related to the nutrient solution and its management make a difference. One approach is to choose the cultivation system based on economics and/or ease of use. However, no matter which system is chosen, the nutrient solution must be suitable for the plant species or growth stage, and must be properly managed to obtain the highest yield and quality. In other words, a proper understanding of the management of nutrient solution is one of the most important factors for successful plant cultivation even under controlled environment conditions.

14.2 Essential elements

There are 92 natural elements, about 60 of which are found in plants (Inden, 2006; Resh, 2013). However, many of these elements are not considered essential for plants. The essential elements have the following characteristics: (1) if the element is absent, the plant shows deficiency symptoms and cannot complete its lifecycle; (2) deficiency symptoms appear in the absence of a specific element; (3) only the specific element can recover the symptoms; another element cannot replace the function; and (4) the element is directly involved in the plant nutrition or plant metabolism (Arnon and Stout, 1939).

In the latest findings in plant nutrition, 17 elements are considered essential for higher plants (Epstein, 1994). These elements are divided into two main classes corresponding to the amount required by the plant. The elements required in relatively large amounts are called macronutrients (major elements), and those required in small amounts are micronutrients (minor elements, trace elements). The macronutrients include nine elements: carbon (C), oxygen (O), hydrogen (H), nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S). The micronutrients include eight elements: boron (B), iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), molybdenum (Mo), chlorine (Cl), and nickel (Ni). Their functions as well as the excess and deficiency symptoms are summarized in Tables 14.1 and 14.2.

Table 14.1 Function, mobility, excess, and deficiency symptoms of macronutrients.	
Nitrogen (N)	
Function:	Constituent of proteins, enzymes, chlorophyll, hormones, nucleic acids, etc.
Mobility:	Easy
Excess:	Nitrate nitrogen ($\text{NO}_3\text{-N}$): Luxuriant growth, succulent growth Ammonium nitrogen ($\text{NH}_4\text{-N}$): Chlorosis, cause of Ca deficiency
Deficit:	Yellowing of lower leaves, color fade-out of whole leaves (reddening in the case of strawberry), decline of plant vigor
Phosphorus (P)	
Function:	Constituent of genes, sugar phosphates, cell membranes, enzymes, ATP, etc. Involved in photosynthesis and respiration
Mobility:	Easy
Excess:	Rare. White spots on cucumber leaves
Deficit:	Growth suppression, dark green coloring of lower leaves and lower part of stem, pigmentation of anthocyanin
Potassium (K)	
Function:	Involved in various metabolic and synthetic reactions through the regulation of internal pH and osmotic potential
Mobility:	Easy
Excess:	Rare. Cause of Ca, Mg deficiency
Deficit:	Outward curling of leaves, yellowing of interveinal part or edge of lower leaves, brown spots on leaves
Calcium (Ca)	
Function:	Constituent of cell walls. Involved in maintenance of construction and function of cell membranes, neutralization of organic acids, transmitter stimuli, etc.
Mobility:	Difficult
Excess:	Rare. Cause of K, Mg deficiency. Cause of micronutrient deficiency by increasing solution pH
Deficit:	Tip-burn, blossom-end rot, black heart, root rot
Magnesium (Mg)	
Function:	Constituent of chlorophyll. Activation of enzymes necessary for protein synthesis, maintenance of ribosome structure
Mobility:	Easy
Excess:	Rare. Cause of K, Ca deficiency
Deficit:	Yellowing of interveinal part or edge of lower leaves
Sulfur (S)	
Function:	Constituent of sulfur-containing amino acids and vitamins. Involved in various redox reactions
Mobility:	Easy
Excess:	Rare. Cause of K, Ca deficiency
Deficit:	Color fade-out or yellowing of lower leaves
<i>(Resh, 2013; Yoneyama et al., 2010)</i>	

Table 14.2 Function, mobility, excess, and deficiency symptoms of micronutrients.	
Iron (Fe)	
Function:	Involved in various redox reactions and electron transfer through the combination with protein
Mobility:	Difficult
Excess:	Rare
Deficit:	Yellowing or chlorosis of interveinal part of new leaves, yellowing of root
Note:	Dark spots on new leaves by rapid absorption of chelate Fe if plants are transferred from soil to soilless culture. Sterilization of nutrient solution by UV rays or ozone gas may precipitate Fe
Boron (B)	
Function:	Involved in the formation of cell walls, maturation of pollen, elongation of pollen tube, translocation of sugars
Mobility:	Difficult
Excess:	Yellowing at edge of lower leaves, browning and brown spots in lower leaves, curling of upper leaves
Deficit:	Malformation of new leaves, poor growth of lateral root, fruit drop, hardening of leaves and stem
Manganese (Mn)	
Function:	Involved in oxygen generation in photosynthetic reactions, extinction of active oxygen, synthesis of fatty acids
Mobility:	Difficult
Excess:	Browning (chocolate brown) of veins of lower leaves, root discoloration
Deficit:	Yellowing or dirty light green coloring of interveinal part of middle/upper leaves, brown spots
Note:	Sterilization of nutrient solution by ozone gas may precipitate Mn
Copper (Cu)	
Function:	Involved in electron transfer I photosynthetic reactions, extinction of active oxygen
Mobility:	Difficult
Excess:	Yellowing of upper leaves, browning of root, poor growth of lateral root
Deficit:	Wilting or necrosis of leaf tip, defoliation
Note:	Care required to prevent elution from piping for heating and cooling, or circulating the solution. Sufficiently contained in tap water
Zinc (Zn)	
Function:	Activation of various enzymes. Involved in the formation of indoleacetic acid
Mobility:	Medium—easy
Excess:	Yellowing of upper leaves, inhibition of root. Cause of Fe deficiency
Deficit:	Suppression of leaf expansion, rosette leaves, yellowing of interveinal part of leaves, yellow-brown spots
Note:	Care required to prevent elution from zinc-plating frame of greenhouse. Sufficiently contained in tap water

Continued

Table 14.2 Function, mobility, excess, and deficiency symptoms of micronutrients.—cont'd

Molybdenum (Mo)	
Function:	Constituent of nitrate reductase. Involved in N ₂ fixation
Mobility:	Medium
Excess:	Yellowing of lower leaves, red-purple coloring of veins
Deficit:	Malformation of leaves, yellowing or necrosis of interveinal part of leaves
Note	Sufficiently contained in tap water
Chlorine (Cl)	
Function:	Regulation of internal pH. Involved in oxygen generation in photosynthetic reactions
Mobility:	Easy
Excess:	Root mortality, fibrous tubers (deterioration of quality)
Deficit:	Suppression of shoot tip growth, mortality
Note:	Sufficiently supplied from nature
Nickel (Ni)	
Function:	Constituent of urease
Mobility:	Unknown
Excess:	Yellowing of leaves, mortality (details are not well known)
Deficit:	Yellowing of leaves, mortality (details are not well known)
<i>(Resh, 2013; Yoneyama et al., 2010).</i>	

Since most fresh vegetables are approximately 90% water, the percentage of dry matter is only about 10% of the initial fresh weight. The dry matter contains 40%–45% carbon (C), 40%–45% oxygen (O), and about 6% hydrogen (H) (Inden, 2006). These essential elements are supplied to the plants as carbon dioxide and water, and it is not usually necessary to consider the supply of carbon, oxygen, and hydrogen as fertilizer. Therefore, excluding these three elements, only six elements (N, P, K, Ca, Mg, S) may be classified as macronutrients. The amount of macronutrients absorbed by vegetables tends to vary in the order of $K > N > Ca > P > Mg$ (Maruo, 2013), and the N or K content in the vegetable leaves is normally higher than that of other minerals (Table 14.3), although the ratio differs depending on the vegetable species (Date, 2012). The mineral content is important information for determining the appropriate composition of the nutrient solution and the management of water and nutrient supply. In addition, vegetables typically have higher Ca requirements compared to other plants. In either case, the essential elements must be artificially supplied to meet the plants' requirements when the supply from nature is insufficient.

14.3 Beneficial elements

Beneficial elements originally referred to the elements essential for specific plant species, or those exhibiting a growth-promoting effect under specific growing conditions (Yoneyama et al., 2010). For higher plants, sodium (Na), silica (Si), cobalt (Co), selenium (Se), and aluminum (Al) are considered

Table 14.3 Mineral concentrations in leaf (%DW).

Vegetable	N	P	K	Ca	Mg
Cucumber	4.62	0.77	3.16	3.86	0.78
Tomato	5.15	0.54	3.78	2.92	0.76
Sweet pepper	5.91	0.51	7.02	1.8.	0.82
Celery	5.74	1.44	7.00	2.06	1.42
Japanese parsley	5.00	1.00	6.92	0.77	0.55
Lettuce	5.36	0.72	7.64	0.79	0.35
Spinach	5.79	0.67	8.38	0.72	1.43

(Date, 2012).

to be the beneficial elements, and their functions as well as the plant species and required conditions are as shown in Table 14.4.

On the other hand, there is another meaning to beneficial elements. The Ministry of Health, Labor and Welfare in Japan specified the recommended values to be obtained from the human diet for 13 minerals, including Se, chromium (Cr), and iodine (I). Co is defined as an essential micronutrient for humans (Ohguchi, 2012), and bromine (Br), fluorine (F), and rubidium (Rb) are present in the human body in relatively high amounts (Yamada, 2010). In other words, it is beneficial for humans that plants contain certain amounts of these elements. Since it is easier to control the amount and timing of the supply of these elements under a controlled environment, they may add value to the products from plant factories.

14.4 Nutrient uptake and movement

The most important physiological role of the plant's roots is to absorb water and nutrients. Normally, nutrients are vigorously absorbed near the root tip and the younger part where the roots grow (Johkan, 2013). The process of nutrient uptake by plants is usually described as two concepts (Lack and Evans, 2001; Resh, 2013). One is the pathway through the apoplast, which consists of interconnecting cell walls and intercellular spaces. Ions are transported through the apoplast (apoplastic transport) and

Table 14.4 Beneficial elements for higher plants.

Element	Function
Sodium (Na)	Growth promotion for table beet
Silica (Si)	Essential for <i>Gramineae</i> plants, addition of disease resistance for cucumber
Cobalt (Co)	Promotion of N ₂ fixation of legumes in N-deficient soil
Selenium (Se)	Beneficial for broccoli, cabbage, etc. (function is not well known)
Aluminum (Al)	Growth-promoting effect for tea plant under low soil pH conditions

(Yoneyama et al., 2010).

reach the Casparian strip where some ions are selected and taken into the endothelial cells by a process that requires respiration. The other is through the ion channel, which is a cellular protein that controls the inflow and outflow of specific ions to and from a cell. The driving force for moving the ions through the channel is the difference between the electrical and chemical potentials, and thus the transport needs no energy. The nutrient ions taken into the cell are transported through the protoplasmic connection (symplastic transport). As a result of these processes, plants can selectively and positively take in a specific ion.

The nutrients move upward with water through the xylem to reach the whole plant body. Eventually, the water-dissolved nutrients penetrate the cell walls, allowing the absorption of nutrients. As an inevitable consequence, the distribution of Ca and B is strongly affected by water movement (Lack and Evans, 2001; Maruo, 2013). The moving force of water is obtained mainly from transpiration flow in the daytime and root pressure flow in the nighttime. Basically, most nutrient ions move only in xylem tissue; however, particular ions are redistributed in the plant body through phloem tissue.

14.5 Nutrient solution

In soilless culture systems, all nutrients are supplied to the plants through a nutrient solution. In short, the nutrient solution is a well-prepared liquid fertilizer. The nutrient solution should fulfill the following conditions: (1) all essential elements for plants are contained; (2) all elements exist in ion form; (3) the concentrations of each ion and the total ions are within the appropriate ranges for normal plant growth; (4) harmful substances and pathogenic microorganisms are not contained; (5) the solution pH is around 5.5–6.5 and stable; (6) the solution can be made using relatively inexpensive fertilizers; (7) the ion concentration, ion ratio, and pH do not fluctuate greatly during the cultivation period, or in the deep flow technique (DFT) and nutrient film technique (NFT); and (8) enough oxygen is dissolved for root respiration.

The composition of the nutrient solution refers to the concentration of each nutrient ion in the solution. Extensive research has been conducted on this topic and many different compositions (formulas) have been designed. Typical formulas widely used in Japan are summarized in Table 14.5. The formula should be chosen depending on the plant type, growth stage, growing season, open or closed system, use of substrate or not, substrate type, target product quality, etc. Nevertheless, the only difference is the proportion of each ion and the concentration. Even a slight change in the nutrient management can have a significant effect on the plant growth and product quality in a soilless culture. Therefore, adequate nutrient management can be achieved by considering not only the composition and concentration of ions but also other conditions, such as the concentration of dissolved oxygen, temperature, flora of microorganisms, etc.

14.6 Solution pH and nutrient uptake

The solution pH (potential hydrogen) refers to the concentration of H^+ ions in the nutrient solution. The solution is neutral if the pH value is at 7, acidic if it is lower than 7 and alkaline if it is higher than 7. The solution pH influences the effectiveness of the nutrients through the change of ion form and/or the solubility. For example, plants mainly absorb P in the form of $H_2PO_4^-$, and more than 80% of P exists as $H_2PO_4^-$ when the solution pH is between 5 and 6. However, P in the form of $H_2PO_4^-$ decreases to 30% when the pH is at 7. Furthermore, Ca easily combines with P to form a precipitate, and the stability of chelate Fe, such as Fe-EDTA, decreases under high pH conditions. The pH is usually

Table 14 5 Typical formulas and compositions of nutrient solutions.

Formula		Concentration (mM)					
		$\text{NO}_3^- \text{N}$	$\text{NH}_4^+ \text{N}$	$\text{PO}_4^- \text{P}$	K	Ca	Mg
Enshi (Nat. Hort. Exp. Sta.)		16	1.3	1.3	8	4	2
Yamasaki	Melon	13	1.3	1.3	6	3.5	1.5
	Cucumber	13	1	1	6	3.5	2
	Tomato	7	0.7	0.7	4	1.5	1
	Strawberry	5	0.5	0.5	3	1	0.5
	Sweet pepper	9	0.8	0.8	6	1.5	0.8
	Lettuce	6	0.5	0.5	4	1	0.5
	Eggplant	10	1	1	7	1.5	1
Hoagland and Arnon (1938)		14	1	3	6	8	4
Holland (rockwool, tomato)		10.5	0.5	1.5	7	3.8	1

(Date, 2012).

controlled between 5.5 and 6.5. However, the desirable solution pH is 4.5–5.5 for leaf onion and some other species to increase Ca and P efficiency.

Fluctuation of the solution pH is mainly caused by the unbalanced absorption of cations and anions by the plants. A plant releases H^+ from the root when it absorbs cations, and OH^- or HCO_3^- when it absorbs anions. Therefore, the solution pH tends to increase when the anion uptake is higher than the cation uptake, and tends to decrease when the cation uptake is higher than the anion uptake. In addition, the pH of the substrate affects the solution pH in substrate culture. Generally, the solution pH tends to increase with an inorganic substrate such as rockwool and rice husk charcoal, and to decrease with an organic substrate such as peat and coir.

14.7 Nitrogen form

Although the main nitrogen form in the nutrient solution is NO_3^- , when it is absorbed by the plant it is reduced to NH_4^+ by nitrate reductase and then assimilated to amino acid. Since the enzyme activity is dependent on the light intensity, the supply of NH_4^+ tends to be less than the amount required by the plant under low light intensity conditions if NO_3^- is the only nitrogen source. Therefore, the use of a small amount of NH_4^+ with NO_3^- usually promotes plant growth under low light intensity. However, if the NH_4^+ absorption rate is higher than the NH_4^+ assimilation rate, NH_4^+ accumulates in the plant cells and becomes harmful due to abnormal N metabolism in the plant. NH_4^+ also inhibits Ca uptake because of antagonism, so the plant easily shows a Ca deficiency. In addition, the characteristics for which the nitrogen form is preferentially absorbed by the plant depend on the plant species, solution pH, solution temperature, etc. Consequently, NH_4^+ is an effective growth promoter for more plant species in soilless culture when: (1) the solution pH is kept constant; (2) a lower NH_4^+ concentration is maintained in the solution; and (3) NH_4^+ is supplied in proper quantities in accordance with the nitrogen assimilation rate of the plants.

14.8 New concept: quantitative management

As described earlier, many different formulas for the nutrient solution have been proposed. However, these formulas have basically been designed with the assumption of controlling the electrical conductivity (EC) or ion concentration in the solution (concentration management). Under these conditions, the quantity of nutrient supply to the plants is influenced by the actual solution volume in the cultivation system. In addition, certain ions such as NO_3^- , H_2PO_4^- , and K^+ tend to be rapidly absorbed by plants under the concentration management conditions, resulting in a large quantity of ions being absorbed by the plants. The yield and quality of products, however, do not increase with the increase in the absorption of these ions after a certain point (luxury absorption). Moreover, the vegetative growth of fruit vegetables tends to be over-luxuriant instead of being reproductive growth, and this unbalanced growth has an adverse effect on the fruit setting and productivity of the plants. Quantitative management of nutrients is a new concept in fertilizer application to prevent luxury absorption by plants (Date, 2012; Terabayashi et al., 2004). When the fertilizer application is quantitatively regulated, the fertilizer is added to the nutrient solution tank once a week or every 2 weeks, and the weight of the fertilizer is determined by preliminary measurement of the nutrient uptake amount by the plant. For example, if the plant absorbs 1 g NO_3^- per day, N fertilizer containing 7 g NO_3^- is added to the solution tank once a week. Even if the nutrient concentration fluctuates under this management method, vigorous absorption of ions from the solution is possible under a wide range of solution concentrations (Maruo et al., 2004). Quantitative management of nutrients has additional advantages because it avoids excessive fertilization. With the price of fertilizer continuing to increase, this management method is considered to reduce the cost of fertilizer. In addition, environmental pollution from draining the nutrient solution can be minimized since the applied fertilizer is entirely consumed by the plants. This method is expected to be widely used with the accumulation of data related to plant nutrient uptake and the development of automatic systems to control the applied amount of fertilizer.

14.9 Can individual ion concentrations be managed automatically?

Each ion in the solution contributes some part to the solution EC. The values have been determined by Kohlrausch's law of independent migration of ions, and therefore the solution EC can be written as the sum of the contribution by each ion (Atkins et al., 2018; Date, 2012). However, the EC calculated by using the values does not match the actual EC of the nutrient solution. Kohlrausch's value has been calculated by assuming "infinite dilution and complete dissociation of the electrolyte." On the other hand, the nutrient solution used in soilless culture is a mixture of multiple ions, and the actual EC is often lower than the calculated EC.

In recent years, some attempts have been made to determine the value of the contribution of each ion in actual nutrient solutions. If this can be achieved, it will be possible to grasp the situation of the nutrient solution more precisely, and then develop a method to control the concentration of each ion in the nutrient solution automatically in commercial production sites.

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15.1 Introduction

Tipburn is a physiological disorder during rapid plant growth involving necrosis at the leaf apex of young developing leaves (Fig. 15.1). This physiological disorder commonly affects many vegetables such as lettuce (*Lactuca sativa* L.), strawberry (*Fragaria × ananassa*), cabbage (*Brassica oleracea* L. var. *capitata*), and Chinese cabbage (*B. pekinensis* Rupr.), and causes major economic losses (Saure, 1998). Tipburn is a serious physiological disorder in the production of lettuce plants in plant factories with artificial lighting (PFALs) as well as greenhouses and open fields.

The major cause of tipburn is often considered to be Ca^{2+} deficiency. Ca^{2+} is a component of cell walls and maintains cell function as a messenger signal, so Ca^{2+} deficiency causes cell death or necrosis because of abnormal cell formation. Internal browning of cabbage and blossom end rot of tomato fruit are also due to Ca^{2+} deficiency in the same way as tipburn. This chapter explains the physiological disorder of Ca^{2+} deficiency, using tipburn of lettuce plants as an example.

**FIGURE 15.1**

Tipburn symptoms in hydroponic butter head lettuce.

15.2 Cause of tipburn

Ca^{2+} deficiency is caused by an imbalance between the Ca^{2+} required by plant cells and the amount supplied by the root zone. In an optimum environment in which plant growth rate increases, Ca^{2+} deficiency tends to occur because the amount supplied cannot keep pace with the increasing amount of Ca^{2+} required by the plant cells. However, tipburn is caused not only by Ca^{2+} deficiency in the plant, but also by the interaction of various factors.

15.2.1 Inhibition of Ca^{2+} absorption in root

The inhibition of Ca^{2+} absorption involves two factors: the low concentration of Ca^{2+} in the root zone and the low absorption ability of Ca^{2+} in the roots. Tipburn often occurs when the plant root cannot absorb Ca^{2+} sufficiently: the plant cells become Ca^{2+} deficient even though the root zone is rich in Ca^{2+} .

Factors preventing the absorption of Ca^{2+} include a drastic pH change in the root zone which damages the roots, unsuitable temperature for root growth, and water and salinity stresses in the root zone. Furthermore, NH_4^+ and K^+ act antagonistically to the Ca^{2+} absorption by root. Under NH_4^+ - and K^+ -rich conditions, the root can absorb more than it needs, so Ca^{2+} absorption is relatively suppressed. A formula for nutrient solution for suppressing lettuce tipburn in hydroponics has been devised (Table 15.1).

15.2.2 Inhibition of Ca^{2+} transfer from root to shoot

Ca^{2+} absorbed by the roots is transferred to shoots by the transpiration stream along with other mineral nutrients. The transpiration stream in xylem is under very strong tension, which pulls the water upward through the root and stem to the leaves. Since the transpiration rate per leaf of immature leaves is less than that of mature leaves, tipburn tends to occur in immature leaves because the supply of Ca^{2+} is insufficient compared with the plant cell requirement. Similarly, suppression of transpiration by a high relative humidity environment and a hot, dry environment in which the stomata close is a major factor preventing the transfer of Ca^{2+} from root to shoot.

The stream of root pressure, which is osmotic pressure of root cells, also transfers the water upward from root to shoot. The tension of the root pressure stream is weaker than that of the transpiration stream, but it plays an important role in transferring water at night. Therefore, low activity of the root due to water and salinity stresses, low temperature, and low oxygen in the root zone also cause Ca^{2+} deficiency.

Table 15.1 Chiba University’s formula for nutrient solution for butter head lettuce (me/L) (Maruo et al., 1992).

Formula	NO_3^-	NH_4^+	PO_4^{3-}	K^+	Ca^{2+}	Mg^{2+}	SO_4^{2-}
Starter fertilizer	12	0	4	8.3	5	2	2
Adding fertilizer	12	1.3	4	8	4	2	2

15.2.3 Competition for Ca^{2+} distribution

Ca^{2+} is an essential component of plant cell walls and is not mobile once it is fixed to the cell wall. Therefore, Ca^{2+} does not move from tissues with sufficient Ca^{2+} to tissues with insufficient Ca^{2+} , and each tissue usually competes for the distribution of Ca^{2+} supplied from the root. One factor affecting the Ca^{2+} distribution is leaf area, and the calcium content in a leaf is strongly dependent on the cumulative transpiration rate. The pulling force of Ca^{2+} from the vascular tissue in immature leaves is weak, because the leaf area and transpiration rate of immature leaves are less than those of mature leaves. If the proportion of mature leaves with large leaf area increases in a plant, the amount of Ca^{2+} distribution in immature leaves relatively decreases.

Table 15.2 Factors causing tipburn in hydroponic lettuce.

Factors	Incidence conditions	Related factors
Shoot • Higher growth rate • Transpiration suppression	Light period and intensity	Relative humidity (vapor pressure deficit) Air current speed Temperature CO_2 concentration Sudden increase in light intensity
Plant • Resistant varieties • Imbalance proportion of mature and immature leaves	Cultivar	Leaf number and area Growth rate
Root • Inhibition of Ca^{2+} absorption • NH_4^+ and K^+ rich in root zone	Nutrient solution	Changes with time of pH

15.3 Countermeasure

Ca^{2+} deficiency is caused by an imbalance between the Ca^{2+} required by plant cells and the amount supplied, and causes physiological disorders such as tipburn (Table 15.2). It is effective to use tipburn-resistant cultivars because the varietal characteristic of Ca^{2+} deficiency varies drastically. Although foliar application of Ca^{2+} is an effective preventive measure, direct application to immature leaves is important, because mature leaves often have enough calcium content. It is also important to slow down the production to some extent because tipburn often occurs under the optimal environment for plant growth. In management, therefore, it is important to find the marginal conditions under which tipburn of only a few percent occurs.

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Functional components in leafy vegetables

16

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16.1 Introduction

Plant factories with artificial lighting (PFALs) enable close control of environmental factors such as light, temperature, humidity, and composition of nutrient solutions. When these factors fluctuate, plants have some ability to acclimate, adjusting their morphological characteristics such as weight, leaf area, stem length, and leaf color, as well as their composition of minerals, pigments, proteins, organic acids, and secondary metabolites. Therefore, environmental control in plant factories enables the production of vegetables with characteristics that better meet customer demands. This chapter introduces the production of functional vegetables by controlling the composition of the hydroponic nutrient solution and the quality of the lighting.

16.2 Low-potassium vegetables

Patients suffering from kidney disease or those undergoing dialysis face restrictions on their potassium intake. However, they can eat fresh salads containing lettuce with a low potassium content. Aizufujikako Co., Ltd., a semiconductor manufacturer since 1967, succeeded in mass-producing low-potassium lettuce for the first time in Japan (Suzuki, 2014). One of their factory's dust-free clean rooms, which receives no solar radiation, was diverted to the cultivation of functional vegetables, including low-potassium lettuce, with almost no renovation required.

The method of cultivating vegetables with a low potassium concentration was established for spinach by Ogawa et al. (2007). The potassium concentration of low-potassium spinach was determined to be about one-fifth (170 mg potassium per 100 g) of that in spinach supplied with the conventional nutrient solution. Starting about 2 weeks before harvest, the supply of potassium was reduced by replacing the KNO_3 in the nutrient solution with HNO_3 , while maintaining the pH at 6.5 with 0.1 M NaOH. Eliminating potassium 2 weeks before harvest did not cause any significant change in fresh weight. However, this restriction of potassium uptake resulted in an increase in sodium concentration in the leaves; the sodium concentration of low-potassium spinach was 13 times higher than that of spinach in the conventional nutrient solution. It is likely that sodium ions were used for maintaining the intracellular osmotic potential instead of potassium ions. This increase in sodium is undesirable for patients suffering from kidney disease or undergoing dialysis.

A modified cultivation method, which became an open patent in 2012, enabled the production of lettuce with low potassium concentration without increasing the sodium concentration (Ogawa et al., 2012). In this method, leaf lettuce was cultivated in a nutrient solution containing neither potassium nor sodium ions from 11 to 17 days before harvesting. The potassium concentration of this lettuce was less than 100 mg per 100 g. According to the standard tables of food composition in Japan, compiled by the Ministry of Education, Culture, Sports, Science and Technology (MEXT), the potassium concentration of regular lettuce is 490 mg per 100 g (MEXT, 2002). Low-potassium lettuce has little bitterness and is expected to be more appetizing to children. In this modified method, the lower limit of the magnesium concentration was up to 5% (w/w) 11–17 days before harvest; sufficient absorption of magnesium by low-potassium lettuce was effective for preventing disease in leaves (Ogawa et al., 2012). Later, Aizufujikako modified other cultivation methods and acquired a patent in 2014 (Matsunaga, 2014). In this method, the concentration of the nutrient solution is managed by carefully controlling the EC value throughout the cultivation period, and the ratio of phosphate to nitrogen concentration in a potassium-containing nutrient solution used in the initial period of cultivation is altered by adding potassium-free nutrient solution in the subsequent stage of cultivation. The potassium concentration of leaf lettuce cultured by this modified method is stable at about one-fourth of that of leaf lettuce cultured by a conventional nutrient solution even in the case of large-scale hydroponics (Matsunaga, 2014).

Aizufujikako is reportedly developing low-potassium melon, tomato, and strawberry (Aizufujikako Co., Ltd., <http://drvegetable.jp/about/>); patients suffering from kidney disease may soon be able to enjoy a fruit salad.

16.3 Low-nitrate vegetables

Plants accumulate the excess nitrogen not used for growth as nitrate in vacuoles. This is considered to be a reserve pool that is utilized during nitrogen starvation. However, although not very toxic itself, nitrate is harmful to human health, and it is hazardous when ingested because it is converted to nitrite in the gastrointestinal tract. Nitrite leads to the formation of nitrosoamines, which are potent carcinogens (Sohár and Domoki, 1980). The nitrate concentration in leafy vegetables can be reduced by eliminating $\text{NO}_3\text{-N}$ in the nutrient solution or replacing it with $\text{NH}_4\text{-N}$ a few weeks before harvest. Further, by promoting nitrate reductase (NR) activity, the nitrate in vacuoles is used for assimilation and the nitrate content in the plants is reduced.

16.3.1 Restriction of feeding nitrate fertilizer to plants

More than 90% of the nitrogen-containing nutrients in most nutrient solutions, including Hoagland's solution and Otsuka-A nutrient solution (Otsuka AgriTechno Co., Ltd., Japan), which is used widely in Japan, are in the form of $\text{NO}_3\text{-N}$. In order to prevent an increase in the nitrate concentration in vegetables, they should be fed a suitable amount of nitrogen fertilizer that can be exhausted during growth. The complete removal of nitrate from the nutrient solution 1 week before harvest results in a 56% decrease in nitrate concentration of celery leaves compared with those grown in regular nutrient solution (Martignon et al., 1994). When plants are deprived of N, they are able to reuse nitrate accumulated in vacuoles for growth, and as a result, the accumulated nitrate decreases (Santamaria

et al., 1998). Cutting N completely 7–10 days before harvest seems to decrease the fresh mass of lettuce leaves at harvest (Santamaria et al., 1998).

Replacing some of the $\text{NO}_3\text{--N}$ in the nutrient solution with $\text{NH}_4\text{--N}$ can decrease the nitrate concentration of vegetables without decreasing yield (Saigusa and Kumazaki, 2014). In general, vegetables cultivated in the field, such as lettuce, spinach, rocket, chicory, and endive, prefer $\text{NO}_3\text{--N}$ over $\text{NH}_4\text{--N}$, and feeding $\text{NH}_4\text{--N}$ is considered to cause stunting. However, some of these plant species that absorb $\text{NO}_3\text{--N}$ preferentially, including lettuce, can grow vigorously in nutrient solution in which the main source of nitrogen is $\text{NH}_4\text{--N}$, provided the pH is kept strictly at 5.5. Their biomass in lettuce plants is almost the same as that of lettuce plants cultured in conventional nutrient solution (Moritugu et al., 1980; Moritugu and Kawasaki, 1982, 1983). When plants take up ammonium ions, they excrete protons into the nutrient solution in order to maintain their internal electric balance. This reduces the pH of the nutrient solution (Tsukagoshi, 2002), and plants sensitive to acidic conditions are injured (Troelstra et al., 1990). However, spinach and Chinese cabbage cultured in a solution in which the main source of nitrogen is $\text{NH}_4\text{--N}$ are stunted even when the pH is held constant, and they seem to be sensitive to both ammonium and pH (Moritugu and Kawasaki, 1983).

In leaf lettuce, the nitrate content was remarkably low without a decrease in yield when available N in the nutrient solution was cut by one-fifth (1375 vs. 6450 ppm for plants fed with the conventional nutrient solution), with the $\text{NO}_3\text{--N}/\text{NH}_4\text{--N}$ molar ratio kept at 1 from transplanting to harvest (Saigusa and Kumazaki, 2014). When chicory plants were transferred from 4 mM $\text{NO}_3\text{--N}$ to 1 mM $\text{NO}_3\text{--N}$ plus 3 mM $\text{NH}_4\text{--N}$ 6 days before harvesting, the nitrate content in leaves decreased by 58% without a decrease in fresh mass compared with growth with no change in nutrient solution (Santamaria et al., 1998).

16.3.2 Reduction in accumulated nitrate by assimilation of nitrate

The nitrate content in tobacco leaves changes diurnally, and the nitrate content at the end of the light period is lower than at the beginning (Matt et al., 1998; Geiger et al., 1998). This diurnal fluctuation in nitrate content seems to be related to NR activity. NR content and activity are low at the end of the night, increase to a maximum at 2–3 h into the photoperiod, and decline during the second part of the photoperiod (Geiger et al., 1998). It seems that the nitrate content declines several hours after NR activity is maximal, so it may be desirable to harvest in the afternoon. NR activity in plants increases with an increase in light intensity (Carrasco and Burrage, 1992). Since the light intensity in PFAL is very low compared with sunlight, it is easy for plants to accumulate nitrate; thus, the nitrogen concentration of the nutrient solution should be kept low.

NR activity is affected by light quality (Jones and Sheard, 1977; Ohashi-Kaneko et al., 2007). NR activity in maize leaves under blue light is higher than under red light, but leaf nitrate content is not affected by light quality (Jones and Sheard, 1977). Nitrate accumulation in plants is also related to nitrate uptake. Blue light promotes stomatal opening (Sharkey and Raschke, 1981; Kinoshita et al., 2001), which may promote nitrate uptake due to an increase in transpiration. Therefore, it may be difficult to regulate nitrate content by only controlling light quality.

16.4 Improving the quality of leafy vegetables by controlling light quality

In general, in PFAL, the minimum light intensity and light period for growing plants with commercial-grade fresh weight are set so as to minimize the electricity cost. Therefore, it is desirable to achieve high productivity and high vegetable quality under limited light intensity. For example, cultivation techniques that enhance antioxidant concentration by controlling the light environment have been developed. This section introduces data on the functional ingredient content of leafy vegetables and herbs irradiated with UV-B, UV-A, or blue light.

16.4.1 Leafy vegetables

Fig. 16.1 shows chlorophyll, carotenoid, L-ascorbic acid, soluble sugar, and nitrate content in the leaves of leaf lettuce, spinach, and komatsuna grown under white, red, and blue light from fluorescent lamps (FLs) and a mixture of red and blue light (the ratio of the number of red FL to the number of blue FL was 1) (Ohashi-Kaneko et al., 2007). The effects of light quality on the concentration of each component and biomass production (data not shown) were quite different depending on the plant species. Irradiation from blue FL alone or a combination of red FL and blue FL can produce high-quality leaf lettuce rich in L-ascorbic acid, but no such blue light effect was observed in spinach or komatsuna. Ooshima et al. (2013) cultivated red leaf lettuce in an environment with a varying ratio of red to blue light from a red light-emitting diode (LED) and a blue LED and observed that both the anthocyanin and ascorbic acid contents increased with an increase in blue light ratio. However, they also noted that when the blue light ratio exceeded 20%, the fresh weight of above-ground tissue at harvest was lower, less than 80 g per plant, which is the commercial-grade fresh weight. Further investigation is required to determine the optimum ratio of blue light and red light that improves the ascorbic acid content in plants that reach commercial-grade fresh weight.

When red leaf lettuce plants are cultivated under irradiation with mixtures of red light and blue light, the leaf anthocyanin content and the expression of genes encoding several enzymes related to the anthocyanin synthesis pathway increase as the blue light ratio increases (Shoji et al., 2010). Anthocyanin synthesis in leaves of red leaf lettuce is induced by UV-B (Park et al., 2007) and UV-A light (Voipio and Autio, 1995). Supplemental irradiation with UV-B light alone or UV-A light alone during the dark period increased the anthocyanin content in the leaves of red leaf lettuce compared with those receiving no supplemental irradiation, and the anthocyanin content was higher under UV-B irradiation than UV-A irradiation (Ebisawa et al., 2008); furthermore, the anthocyanin content in leaves grown under supplemental irradiation of UV-B plus $60 \mu\text{mol m}^{-2} \text{s}^{-1}$ of blue light during the dark period was seven times higher than that of plants grown with no supplemental irradiation. Since high-quality leaf lettuce rich in anthocyanin content can be shipped if harvested in the first half of a light period, this is a useful technology.

16.4.2 Herbs

The functional ingredients in herbs are mainly products of secondary metabolism, such as essential oils, polyphenols, carotenoids, anthocyanins, and alkaloids. The secondary metabolite ingredients of

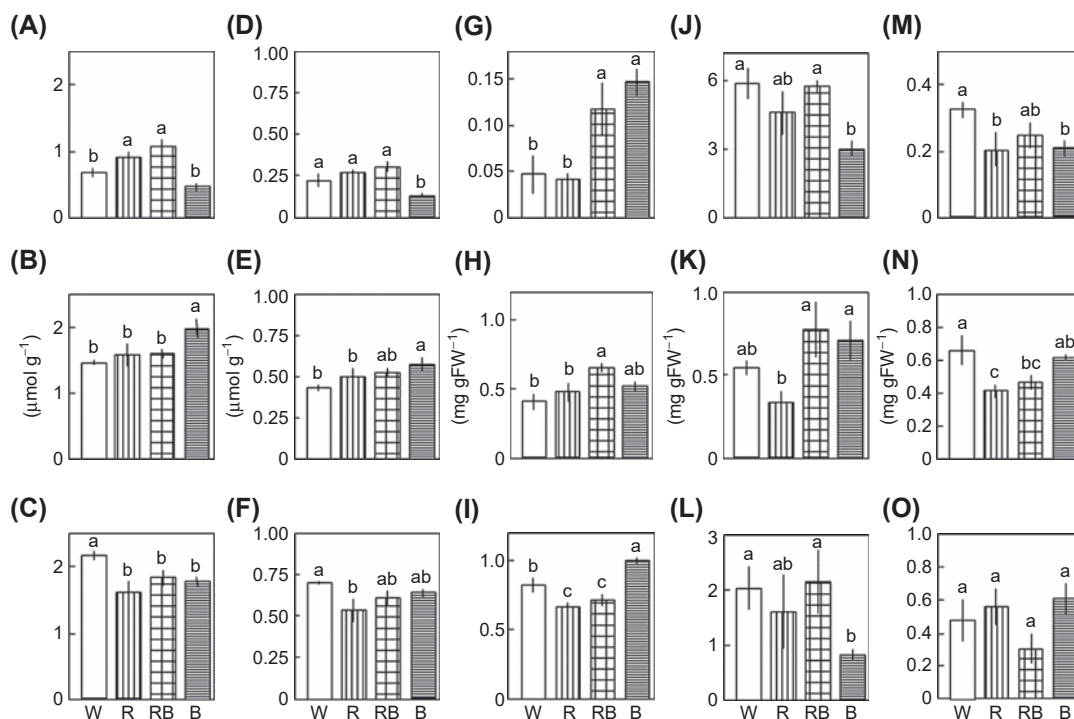


FIGURE 16.1

Chlorophyll (A, (B, C), total carotenoid (D, (E, F), L-ascorbic acid (G, (h, i), soluble sugar (J, K, L), and nitrate (M, N, O) in the leaves of leaf lettuce (A, D, G, J, M), spinach (B, E, H, K, N), and komatsuna (C, F, I, L, O) grown under white light (W), red light (R), blue light (B) from FL or a mixture of R and B (RB) at 37 days after germination for leaf lettuce and spinach and 32 days after germination for komatsuna (Ohashi-Kaneko et al., 2007). The vertical bars indicate the SE ($n = 4$). Means with different letters within each panel are significantly different at the 5% level by LSD.

plants function as defensive chemical substances. For example, when plants are exposed to biotic stress, such as being eaten by insects or animals, synthesis of essential oils is promoted (Koseki, 2004). Production of secondary metabolites is also promoted by abiotic stress, such as high temperature, low temperature, dryness, and UV light irradiation. In addition, light quality triggers the synthesis of secondary metabolites (Koseki, 2004).

UV irradiation raises the essential oil concentration in leaves of herbs. Hikosaka et al. (2010) observed that the limonene and *l*-menthol concentrations of the upper leaves of Japanese mint plants grown under white light from FL supplemented with UV-B light were, respectively, 1.5 and 2 times higher than in plants grown under white light with no supplemental UV-B light. When sweet basil grown in a glasshouse into which sunlight enters is irradiated with supplementary UV-B in the early morning, levels of several essential oils including eugenol and linalool were enhanced compared with no UV-B supplementation (Johnson et al., 1999).

We have also investigated the effects of visible light quality on biomass production and essential oil concentration of perilla, coriander, and rocket. Fig. 16.2 shows the main essential oil content of perilla and coriander plants grown under different lighting conditions (Ohashi-Kaneko et al., 2013). Red and blue LEDs and white FL (control) were used as the light sources for cultivation. The biomass production of perilla plants grown under blue light was much smaller than that under red light. The concentration of perillaldehyde, which makes up 50% of the essential oil, in the leaves of the perilla plants grown under blue light was 1.8 times higher than that of the plants grown under red light. The

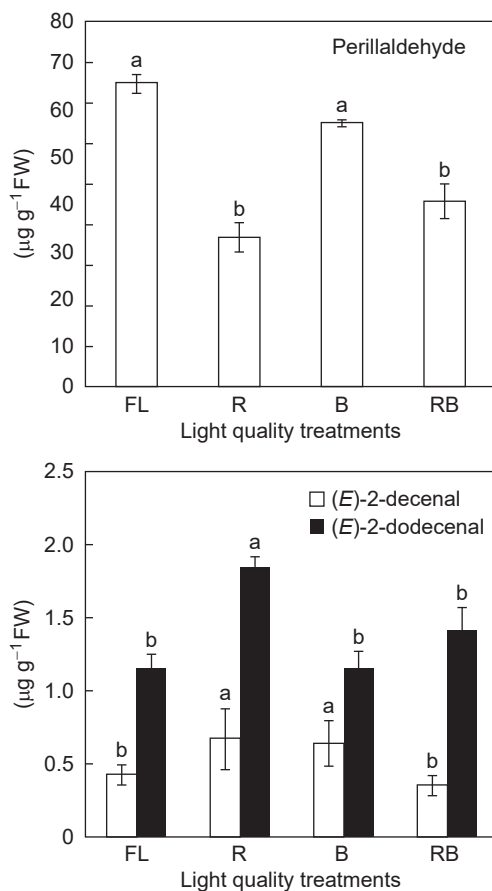


FIGURE 16.2

Perillaldehyde content in the leaves of perilla plants at 35 days after transplanting (upper panel) and (*E*)-2-decenal and (*E*)-2-dodecenal contents in the shoots of coriander plants at 21 days after transplanting (lower panel) (Ohashi-Kaneko, 2013; Ohashi-Kaneko et al., 2013). These plants were grown under white light from FL (FL), red light (R), blue light (B) from LED, or a mixture of R and B (RB). The vertical bars indicate the SE ($n = 2-3$ for perilla plants, $n = 3$ for coriander plants). Means with different letters within a panel are significantly different at the 5% level by the Tukey–Kramer honest significant difference (HSD) test.

biomass production and (*E*)-2-decenal and (*E*)-2-dodecenal concentrations were highest in coriander grown under red light (Ohashi-Kaneko et al., 2013). To produce high-quality coriander, the concentration of heptane, (*E*)-2-hexenal, and octanal, which give it a fresh grassy fragrance, should also be raised (Kohara et al., 2006). Therefore, we plan to examine the effects of light quality on the composition of these essential oils. The smell of salad rocket resembles that of sesame seeds, and is considered to originate in essential oils such as benzaldehyde with an almond-like flavor, furfural with flavors resembling almond and fresh baked bread (Jirovetz et al., 2002), and anethol (Awano et al., 2006). The composition of its essential oil differs depending on the light quality of the environment in which the rocket plants are cultivated (Ohashi-Kaneko et al., 2013). By detailed comparison of the composition of the essential oil and the flavor and taste of the leaves under different lighting conditions, control of the light quality will enable the quality of rocket to be adjusted. It may soon be possible to produce herbs matched with their purpose, such as cooking materials, raw materials for fragrances, and medicinal materials, in an enclosed artificially lit plant factory.

16.5 Conclusion

Since methods for producing low-potassium and low-nitrate vegetables are reasonably well established, the next step is stable mass production. In addition, controlling the light quality will be useful for increasing biomass productivity and also the concentration of functional ingredients of vegetables and fresh herbs, although the most effective light treatment will depend on the species. The optimum light quality conditions for growing plants with commercial-grade fresh weight and rich in functional ingredients differ, and include variations in light intensity and light period. We plan to analyze the growth of plants cultivated under various lighting conditions.

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Medicinal components

17

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17.1 Introduction

Medicinal herbs were the primary healthcare agents for many centuries before the advances of modern medicine and are still used worldwide as a significant part of the healthcare system. In a recent report of the World Health Organization, the percentage of the population which has used plant-based medicine at least once is 48% in Australia, 70% in Canada, and 75% in France ([WHO report: Traditional Plants, 2003](#)). Currently, up to 80% of the population in Africa and 40% in China use traditional medicines to meet their healthcare needs ([WHO report: Traditional Plants, 2003](#)). As a result, international trade in medicinal plants has become a major part of the global economy and demand is increasing in both developing and industrialized nations. According to a recent report by Global Industry Analysts, the global herbal supplements market was set to reach \$107 billion by 2017 ([Global Industry Analysts Report, 2014](#)). However, this explosive growth of the consumption of plant-based medicines has been accompanied by issues of quality and consistency, compromising the safety and efficacy and leading to serious health issues ([Zobayed et al., 2005a](#)). These issues include: (1) adulteration and contamination with misidentified plant species; (2) contamination with plant and soilborne microbial and environmental pollutants leading to wide variation in the concentration of medicinal metabolites in the plant tissues; (3) genetic variability of seed-grown medicinal plants leading to variations in medicinal contents; and (4) medicinal metabolites from wild-collected plants or from field cultivation can be influenced by seasonal variations, as well as variations in growing conditions such as temperature, photoperiod, sunlight (UV and other light qualities), light intensity, water content, soil pH, soil nutrient condition, etc. However, there is virtually no cultivation of medicinal plants on any significant scale worldwide and the current procedure for preparing medicinal plant agents involves mainly harvesting wild plants. In a report, [Williams \(1996\)](#) estimated that about 99% of the 400–550 species currently sold for use in traditional medicine in Africa originate from wild sources. Therefore, it is necessary to develop new technologies to ensure the efficacy and safety of medicines based on plants and to maximize the biomass and metabolite contents in plants.

17.2 Growing medicinal plants under controlled environments: medicinal components and environmental factors

Environmental factors such as temperature, relative humidity, light intensity, light quality, water content, minerals, and CO₂ concentration in the air influence the growth of a plant and production of medicinal metabolites. Recent research indicates that growing medicinal plants under controlled environments with artificial light can ensure the efficacy and safety of the medicinal plant products, ensure year-round harvesting of products, and maximize biomass production by optimizing nutrient uptake and environmental factors such as temperature and CO₂ concentration. A number of studies have been conducted in recent years to manipulate environmental factors to optimize medicinal components while growing under controlled environments.

17.2.1 CO₂ concentration and photosynthetic rates

Among the environmental factors, CO₂ concentration is one of the most important affecting medicinal components in plants under controlled environments. A number of studies have been conducted on *Hypericum perforatum* plants growing under a controlled environment with CO₂ enrichment; those studies showed that CO₂ can enhance biomass and secondary metabolite production by increasing net photosynthetic rates. For example, Mosaleeyanova et al. (2005) showed that medicinal metabolite contents (mg/plant) in the leaf tissues were significantly higher in plants grown under controlled environments than those in the field (control). They found that hypericin and pseudohypericin contents in plants grown under controlled environments were 30 and 41 times greater, respectively, than those of the field-grown plants. They also showed that hypericin and pseudohypericin contents in the leaf tissues increased with increasing photosynthetic rate under elevated levels of CO₂. In another study, Zobayed and Saxena (2004) reported that growing *H. perforatum* plants under a controlled environment with CO₂ enrichment increased the hypericin, pseudohypericin, and hyperformine concentrations. A positive relationship between photosynthetic rate and medicinal composition of *H. perforatum* has also been described (Zobayed et al., 2006). These studies showed that in plants grown under elevated CO₂ concentrations, the leaf photosynthetic rates, and the contents of medicinal components increased. In *Scutellaria baicalensis*, a CO₂ enrichment system showed higher concentrations of wogonin, baicalein, and baicalin in plant tissues compared with a nonenriched system (Zobayed et al., 2004).

17.2.2 Temperature stress

Temperature stress is known to cause many physiological, biochemical, and molecular changes in plant metabolism and alter the production of secondary metabolites in plants. Elevated temperatures reduce stomatal conductance and thus reduce photosynthesis and growth of many plant species (Berry and Bjorkman, 1980). The photochemical efficiency of photosystem II (PSII) also decreases at elevated temperatures, indicating increased stress (Gamon and Pearcy, 1989; Maxwell and Johnson, 2000). When plants are stressed, secondary metabolite production may increase because growth is often inhibited more than photosynthesis, and the carbon that is fixed but not allocated to growth is instead allocated to secondary metabolites (Mooney et al., 1991). Several studies have examined the effects of increased temperatures on the production of secondary metabolites in plants, but most of

these studies yielded contradictory results. Some report that secondary metabolites increase in response to elevated temperatures (Litvak et al., 2002), while others report that they decrease (Snow et al., 2003). In the case of *H. perforatum*, plants grown under controlled environments for 70 days followed by low-temperature (15°C) treatment for 15 days showed a reduction of photosynthetic efficiency and the maximum quantum efficiency of PSII photochemistry of the dark-adapted leaves ($\phi_{\text{max}}^{\text{p}}$). High-temperature (35°C) treatment decreased net photosynthesis and maximum quantum efficiency of PSII as well, but increased the leaf total peroxidase activity and also increased the hypericin, pseudohypericin, and hyperforin concentrations in the shoot tissues (Zobayed et al., 2005b). These results provide the first indication that temperature is an important environmental factor to optimize secondary metabolite production in *H. perforatum* and controlled environment technology can allow the precise application of such specific stresses.

17.2.3 Water stress

Water stress is known to increase the concentrations of secondary metabolites in plant tissues and a severe water stress condition may cause oxidative stress due to the formation of reactive oxygen species and photoinhibitory damage. A detailed study was conducted by Zobayed et al. (2007) to evaluate the changes in physiological status, especially the photosynthetic efficiency and the medicinal component profile of the leaf tissues of *H. perforatum* plants exposed to water stress. In the leaf tissues of plants grown under a water stress condition, both hypericin and pseudohypericin concentrations reduced with time and the concentration was significantly lower than that of the control; in contrast, the hyperforin concentration increased significantly. The net photosynthetic rates of the leaves of plants grown under a water stress condition were significantly lower than those of the control. The maximum quantum efficiency of PSII photochemistry ($\phi_{\text{max}}^{\text{p}}$) of the dark-adapted leaves was similar for both wilted and recovered plants although these values were significantly lower than those of the control. The leaf tissues of the plants under a water stress condition had a significantly higher capacity to detoxify oxygen radicals with an approximately 2.5-fold increase over the antioxidant potential of the leaves of nontreated (control) or recovered plants. In another study, Abreu and Mazzafera (2005) showed that water stress increased the levels of medicinal compounds such as betulinic acid, quercetin, rutin, 1,5-dihydroxyxanthone, and isouliginosin *B* in *Hypericum brasiliense*, an important medicinal plant. They concluded that there is a reallocation of carbon, with water-stressed plants showing a reduction in growth while the levels of the compounds increased.

17.2.4 Spectral quality and UV radiation

Glycyrrhizin, the major bioactive component of *Glycyrrhiza uralensis*, is widely used as a natural sweetener. In a recent study, Afreen et al. (2006) evaluated the effects of different spectral qualities of light including red, blue, white, and UV-B radiation on the production of glycyrrhizin in a controlled environment. Plants were grown under artificial lights with elevated CO₂ concentration and assigned to red, blue, and white light treatments. The concentrations of glycyrrhizin quantified in the root tissues were highest in the plants grown under red light compared with white or blue light. In plants exposed to UV-B radiation (3 days at 1.13 W m⁻²; wavelength: 280–315 nm) while growing under a controlled environment, the concentration of glycyrrhizin increased significantly in the root

tissues of 3-month-old plants. These results indicate another advantage of growing plants in a controlled environment, i.e., a high concentration of secondary metabolite production can be achieved within a short production period. Exposure of plants to UV radiation results in multiple responses including increased synthesis of UV-screening pigments, as well as reinforcement of the antioxidant system and other defense mechanisms. Many plants are capable of avoiding UV radiation by accumulating UV-filtering flavonoids and other secondary metabolites; for instance, epidermal flavonoids are enhanced in response to increased UV-B (Bornman et al., 1997). The synthesis of the basic skeletons for active secondary metabolites is dependent on the carbon assimilated during photosynthesis and the rate of photosynthesis is known to be influenced by light intensity, spectrum of the available light, duration of light, etc. Plant responses to red, blue, or UV radiation induce different expressions via signal transduction pathways using signal transducing photoreceptors, which are a switch for controlling the expression of specific genes involved with growth, developmental processes, and secondary metabolism in plants (Jenkins et al., 1995). Cosgrove (1981) mentioned that blue light reduces cell expansion and thus inhibits leaf growth and stem elongation. This growth inhibition is mediated by blue light photoreceptors and is considered distinct from inhibitory phytochrome effects.

Melatonin (*N*-acetyl-5-methoxytryptamine) is known to be synthesized and secreted by the pineal gland in vertebrates. Evidence for the occurrence of melatonin in the roots of *G. uralensis* plants and

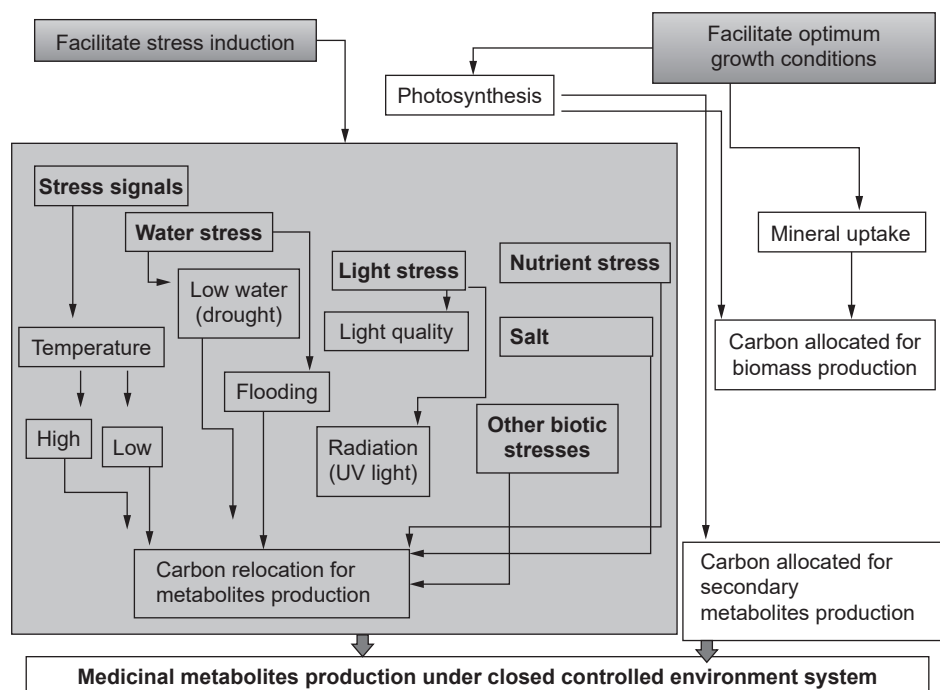


FIGURE 17.1

Pathways facilitating the production of medicinal metabolites under a closed controlled environment system.

the response of this plant to the spectral quality of light including red, blue, and white light (control) and UV-B radiation (280–315 nm) under controlled environment systems for the synthesis of melatonin were investigated in a recent study (Afreen et al., 2007). Melatonin concentrations were highest in plants exposed to red light and varied depending on the wavelength of the light spectrum in the following order: red $\geq$ blue $\geq$ white light. Interestingly, in a more mature plant (6 months) melatonin concentration was increased considerably. The concentration of melatonin quantified in the root tissues was highest in the plants exposed to high-intensity UV-B radiation.

17.3 Conclusion

The production of medicinal plants under controlled environments described in this chapter represents significant progress for phytopharmaceutical production. The production of medicinal plants in a closed controlled environment system has several advantages: (a) plants can be grown in sterile, standardized conditions and are free from biotic and abiotic contamination, (b) uniform plant growth with consistent plant material can be achieved, and (c) consistent biochemical profiles can be achieved with uniform production of metabolites. Closed systems can ensure optimum environmental conditions to maximize biomass production (Fig. 17.1) and facilitate the induction of stresses, thus inducing the reallocation of carbon to the production of medicinal metabolites (Fig. 17.1). The adaptation of the growing system described here may facilitate the development of safe, consistent, and high-quality phytopharmaceutical products of medicinal plants.

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Production of pharmaceuticals in a specially designed plant factory

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18.1 Introduction

Plant factories with artificial lighting (PFALs), where leafy vegetables are cultivated until harvest in closed plant production systems with artificial lighting (CPPSs), were proposed, developed, and implemented in Japan during the 1980s. During the 1990s, the products from these factories received high evaluations by the food service industry, to which they primarily catered. During the 2000s, commercial production of nursery plants of fruits and vegetables, flowers, and ornamental plants was initiated in CPPSs or PFALs (see Chapter 22). PFALs also provide good cultivation systems for the production of plants for pharmaceutical use.

Recently, genetically modified (GM) plants have attracted much attention because of their use in the production of valuable materials, such as pharmaceutical proteins, for humans or livestock. Pharmaceutical products that have been or are being developed include oral vaccines for humans or livestock, agents that prevent lifestyle-related diseases, substances with antimicrobial or antiinflammatory effects, and functional proteins and secondary metabolites.

The production of pharmaceutical materials by using GM plants (plant-made pharmaceuticals, PMPs) has advantages over conventional production methods using animals or microorganisms (Daniell et al., 2001; Ma et al., 2003), such as (1) low risk of contracting infectious diseases from animals or microorganisms used, (2) elimination of the need to maintain a cold chain, (3) low production cost, (4) ease of large-scale production, and (5) utilization as functional food.

Food crops can be utilized for the production of valuable materials because their edible components have a low risk of transmitting infectious diseases. In Japan, research groups have introduced functional protein-encoding genes into rice, potato, soybean, lettuce, tomato, and strawberry plants (Table 18.1) [for oral vaccine see Nochi et al. (2007); for miraculin see Sugaya et al. (2008) and Kim et al. (2010)]. Expression of the inserted DNA and accumulation of the required protein in the target plant organ are significantly influenced by plant and climatic conditions (Stevens et al., 2000). Therefore, a highly controlled environmental system is required to achieve an annual production of a valuable material with consistent quality.

A CPPS is ideal for the production of medicinal substances that have been approved by pharmaceutical law. Advantages of the CPPS over open fields include: (1) stable plant production under complete environmental control, (2) efficient use of water and CO₂ gas, (3) fulfillment of the good

Table 18.1 Pharmaceutical materials developed or being developed in Japan.			
Type	Target	Material	Host plant
Oral vaccine	Human	Vaccine for cholera	Rice
	Human	Influenza vaccine	Rice
	Livestock	Vaccine for swine edema disease	Lettuce
Pharmaceutical material	Livestock	Bird influenza vaccine	Potato
	Human	Human thioredoxin	Lettuce
	Pet animal	Canine interferon for periodontal disease	Strawberry
Functional protein	Human	Lactoferrin	Strawberry
	Human	Miraculin	Tomato
<i>The materials were selected from research projects subsidized by the METI as “Development of fundamental technologies for production of high-value materials using transgenic plants” (2006–10).</i>			

manufacturing practice (GMP) specifications, and (4) low risk of gene diffusion. Because responses of GM plants to environmental conditions have not been investigated, it is necessary to research the physiological characteristics of the plants and establish suitable cultivation methods for each plant under artificial conditions.

The author’s research group developed a CPPS for stable accumulation of high concentrations of desired functional proteins in the edible components of strawberry and rice plants. The GM strawberry plant accumulates a functional protein in the achenes and the fruit, which is known to prevent lifestyle-related diseases. The GM rice plant accumulates an oral vaccine in the protein body of the seed. This chapter summarizes the production system and appropriate environmental conditions for plant production of valuable materials in large quantities.

18.2 Candidate crops for PMPs

Considering the selection of plant species, established genetic engineering technology for the plants is primarily important, and the mechanism by which a plant accumulates the target material should also be investigated. For commercialization of a large-scale production system, reduction in labor in terms of cultivation management and easy installation of mechanization and automation are also of importance.

We have tested a variety of food crops in the CPPS and calculated the production efficiency of photoassimilates per unit light energy for rice, strawberry, lettuce, and tomato from our experimental data (Table 18.2). Leafy vegetables and fruits are cultivated in commercial PFALs and greenhouses. However, from the viewpoint of productivity, the production efficiency of photoassimilates per unit light energy does not differ significantly among food crops. Therefore, besides vegetables, crops such as cereals, pulses, and potatoes are candidate crops. For example, cereal and pulse crops are suitable for the production of valuable materials derived from carbohydrates and proteins, and cereal crops and potatoes can be stored for long periods at normal temperatures. Leafy vegetables have a high harvest

Table 18.2 Comparison of candidate crops for PMPs based on experimental data.

		Rice	Strawberry	Lettuce	Tomato
PPF	$\mu\text{mol m}^{-2} \text{s}^{-1}$	800	300	200	600
Light period	h day^{-1}	12	16	16	12
Daily PPF (DLI)	$\text{mol m}^{-2} \text{day}^{-1}$	34.6	17.3	11.5	25.9
Integrated PPF	$\text{mol m}^{-2} \text{year}^{-1}$	12,440	6220	4150	9330
Cultivation period	Days	100	90	30	90
Edible biomass per cultivation ^a	gFW m^{-2}	800	3200	2500	7500
Harvest index		0.5	0.5	0.9	0.5
Dry matter ratio	%	85	10	5	6
Total dry biomass per cultivation	gDW m^{-2}	1360	640	139	900
Number of cultivations		3.6	4	12	4
Total dry biomass per year	$\text{gDW m}^{-2} \text{year}^{-1}$	4896	2560	1667	3600
Production efficiency of photoassimilates per unit light energy	g mol^{-1}	0.39	0.41	0.40	0.39

^aHighest production was calculated for optimal cultivation management at a light condition based on our experimental data.

index and a short cultivation period, and we do not need to focus on the diffusion of pollen because they are harvested before flowering. Fruits originally have functional compounds such as polyphenols; therefore, GM fruit plants may have multiple positive effects if plant modification is designed to accumulate a valuable material that can be used for the prevention of lifestyle diseases.

18.3 Construction of GM plant factories

We constructed two CPPSs with artificial lighting for stable accumulation of high concentrations of desired functional proteins in the edible components of strawberry and rice plants. Fig. 18.1 shows the facility design and air and water flow of a closed rice production system. The production system is an advanced model of a commercial PFAL using only artificial light. However, the design is unique from the viewpoint of transgenic crop management. The system must have facilities to prevent diffusion of plant parts, such as pollen, and to inactivate the unused parts of the crop. If the system specifications meet the standards, an ideal environment for GM plant production can be provided.

With regard to environmental control, spatial uniformity of light, temperature, humidity, and gas in a plant canopy is crucial to the production of a material bearing consistent quality. The CPPS can be used to manipulate not only the aerial conditions but also the root zone conditions. By using hydroponics, the nutrient solution can be optimized for each growth stage. Therefore, the system can provide the plant with a variety of artificial stimuli and physiological stresses to maximize accumulation of the target material. Because the system provides appropriate growth conditions and an agrochemical-free

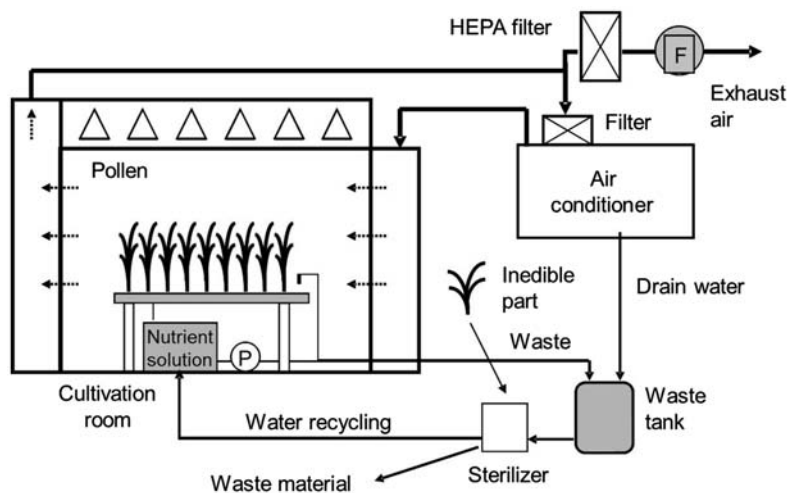


FIGURE 18.1

Facility design and air and water flow in the typical cultivation room of a CPPS.

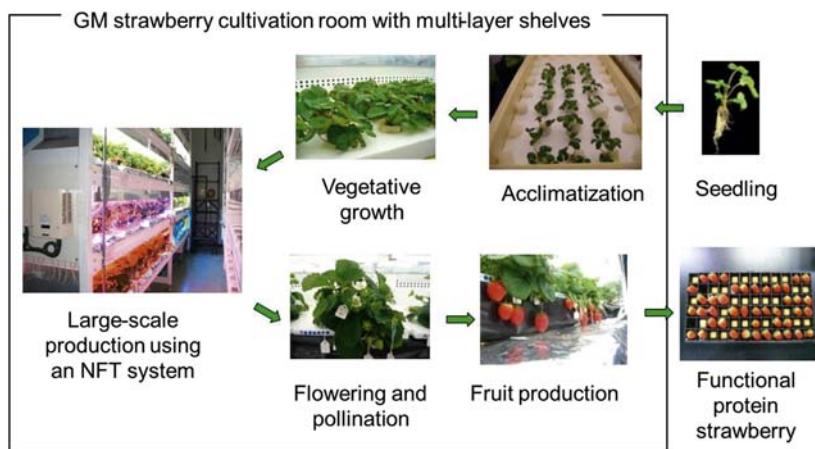


FIGURE 18.2

Cultivation of GM strawberry plants in a CPPS.

environment by blocking pest invasion, agronomic plant traits to overcome natural environment-related problems are not required.

We developed a prototype of a strawberry cultivation room (20 m²) equipped with multilayer shelves with white fluorescent lamps (FHF32-EX-N-H; Panasonic Electric Works Co., Ltd.) and a commercial NFT hydroponic system for GM strawberry production (Fig. 18.2). We used non-GM everbearing strawberry (*Fragaria* × *ananassa* Duch. cv. “HS138”) plants for the cultivation

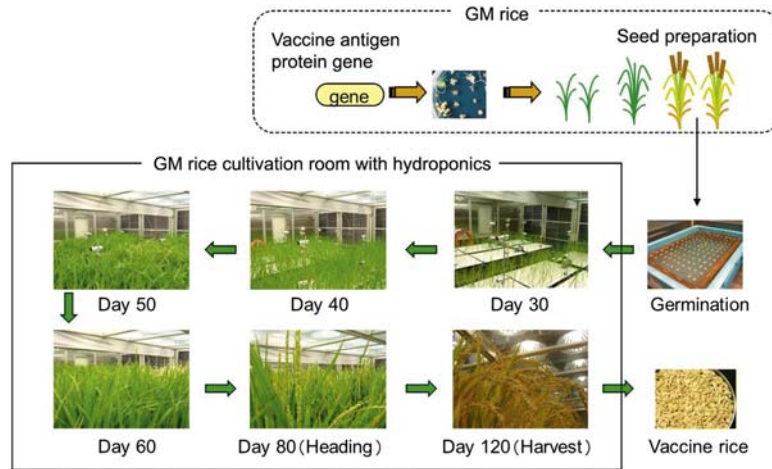


FIGURE 18.3

Cultivation of GM rice plants in a CPPS. The day is an example of a standard cultivation condition.

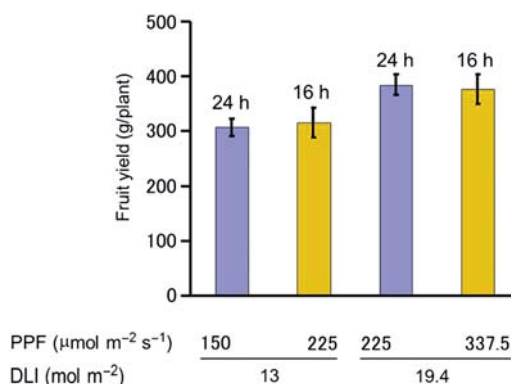
experiment. The seedlings were derived from the micropropagation of stem meristems (Hikosaka et al., 2009; Miyazawa et al., 2009) and were then cultivated in the room. Air temperature, relative humidity, and CO_2 concentration in the room could be regulated to suitable levels. In the flowering stage, pollination was carried out manually every 2–3 days.

We developed a prototype of a rice cultivation room with a lighting system by using a high-intensity light source for GM rice production (Fig. 18.3). This prototype has a hydroponic cultivation area of about 15 m^2 , a height of about 2 m, and is equipped with 56 ceramic metal halide lamps (M400FCEH-W/BUD/H0; Iwasaki Electric Co., Ltd.). The maximum light intensity is about $1200 \mu\text{mol m}^{-2} \text{s}^{-1}$ of photosynthetic photon flux (PPF) at 1 m above the floor surface. It is possible to vary the light intensity to the required level within a range of 65%–100% by using a light control system. Furthermore, the thermal conditions of the cultivation area can be controlled by separating the lamp and cultivation spaces with glass and circulating air exhausted from the cultivation space to the lamp space. Non-GM rice (*Oryza sativa* L., Nipponbare) plants were used for material plants in the cultivation experiment.

18.4 Optimization of environment conditions for plant growth

18.4.1 Strawberry

We adopted the same approach as that of the rice plants to establish optimal light conditions for the strawberry plants in the CPPS. According to the results of the growth experiment using various air temperatures and CO_2 concentrations, we set the average daily temperature at 23°C and the CO_2 concentration at $1000 \mu\text{mol mol}^{-1}$. Fig. 18.4 shows the fruit yield of an individual plant for 35 days from when the first flower was fertilized. A DLI (daily light integral) of $19.4 \text{ mol m}^{-2} \text{day}^{-1}$ produced 380 g of fruits. With three cultivations per year and a planting density of five plants m^{-2} , the annual yield would be 42% greater than the average yield of greenhouses. The results indicate that suitable

**FIGURE 18.4**

Fruit yield of strawberry plants grown in the CPPS under different PPF, light period, and DLI conditions.

cultivation conditions in the CPPS enhance photosynthesis of strawberry plants and subsequently facilitate maximum fruit production.

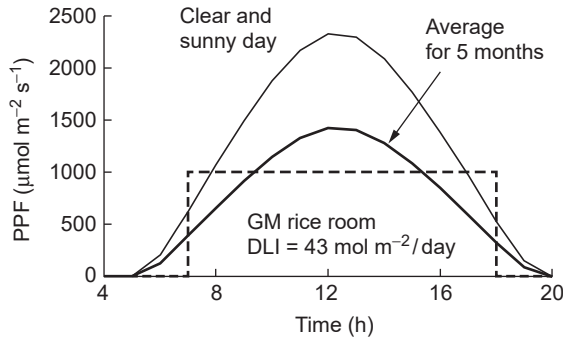
We studied the effects of light quality on plant growth and concentration of human adiponectin (hAdi) in transgenic everbearing strawberry (*Fragaria* $\times$ *ananassa* Duch. “HS 138”) (Hikosaka et al., 2013). The hAdi plants in the flowering stage were exposed to three different light qualities (white, blue, and red) for a 16-h light period under fluorescent lamps until the fruits were harvested. The hAdi concentration on a fresh-weight basis in plants grown under red light condition was significantly highest among all treatments.

18.4.2 Tomato

Kato et al. (2010) created a new variety of dwarf tomato suitable for high productivity of fruits that contain the target pharmaceutical material in a closed cultivation system under stable environmental conditions. We investigated the effects of light intensity on tomato fruit yield and the accumulation of recombinant miraculin, a taste-modifying glycoprotein, in transgenic tomato fruits (Kato et al., 2011). Plants were cultivated at various PPFs of 100–400 $\mu\text{mol m}^{-2} \text{s}^{-1}$ under white fluorescent lamps in the CPPS. Miraculin production per unit of energy used was the highest at 100 $\mu\text{mol m}^{-2} \text{s}^{-1}$; however, miraculin production per unit area was the highest at 300 $\mu\text{mol m}^{-2} \text{s}^{-1}$. The commercial productivity of recombinant miraculin in transgenic tomato fruits largely depended on light conditions in the PFAL.

18.4.3 Rice

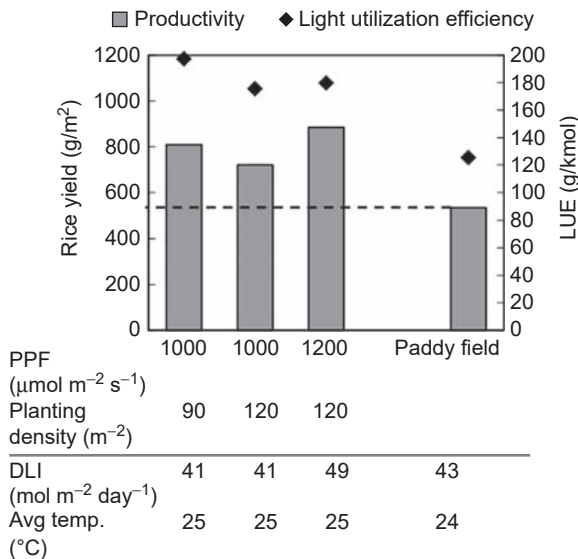
To determine the optimal light conditions for rice plant production, we analyzed light conditions of the conventional rice cultivation method in paddy fields and established a new lighting strategy. In Hikone City, Shiga Prefecture, located in the center of Japan’s main island, the DLI exceeds 65 $\text{mol m}^{-2} \text{day}^{-1}$ on a clear and sunny day in mid-June. However, the average DLI in paddy fields for approximately 5 months from transplanting to harvest is 43 $\text{mol m}^{-2} \text{day}^{-1}$ (Fig. 18.5). In the CPPS, it is not necessary to recreate a typical sunlight curve of 43 $\text{mol m}^{-2} \text{day}^{-1}$ with a maximum intensity of


FIGURE 18.5

Light conditions of conventional cultivation of rice in paddy fields and a lighting strategy specialized for a CPPS.

$1400 \mu\text{mol m}^{-2} \text{s}^{-1}$ because initial costs of lamps and ballasts are high and air temperature and humidity control becomes relatively complicated with large changes in light intensity. Consequently, we set light intensity at $1000 \mu\text{mol m}^{-2} \text{s}^{-1}$ PPf and light period at 12 h day^{-1} so the DLI reached $43 \text{ mol m}^{-2} \text{day}^{-1}$. The air temperature in the light period was controlled at 27°C to maximize both photosynthetic and growth rates. The air temperature in the dark period was set at 23°C , so the average daily air temperature was 25°C . The relative humidity was set at 70%, and the CO_2 concentration was set at $400 \mu\text{mol mol}^{-1}$.

Rice plants were cultivated under various planting densities and DLI conditions. The results showed that the yield of rice grown in the room was 40%–60% greater than the average yield of the cultivar grown in paddy fields in Japan (Fig. 18.6). The main reason was probably that there were no


FIGURE 18.6

Comparison of productivity and light utilization efficiency of rice plants grown in the CPPS and in paddy fields.

cloudy or rainy days in the CPPS so that the plants photosynthesized continuously under optimal conditions of light intensity and air temperature. This was supported by higher light utilization efficiencies of the three treatments tested in the room. Further, the efficiency at $1000 \mu\text{mol m}^{-2} \text{s}^{-1}$ PPF was higher at a planting density of 90 plants m^{-2} than at a density of 120 plants m^{-2} . This means that an optimal planting density for rice production exists under certain environmental conditions, as shown in paddy fields.

18.5 Concluding remarks

Manipulation of aerial environmental factors such as light and air temperature is a key technique to promote accumulation of desired functional proteins. For maximally utilizing the CPPS for accumulating a valuable material, plants that can be grown under continuous lighting and have the potential to induce the target material in response to aerial environmental stresses are very promising. Plant production using this technology is not a part of agriculture; it is a new plant-based industry that combines molecular biology and environmental engineering.

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PART

System design,
construction,
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Plant production process, floor plan, and layout of PFAL

19

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19.1 Introduction

The floor plan of a plant factory with artificial lighting (PFAL) and layouts of equipment and culture (or cultivation) beds are designed to achieve efficient operations by workers and smooth flows of materials such as the plants and supplies in the plant production system. In addition, it is essential that the PFAL be designed and operated to maintain a high level of sanitation for food safety.

However, PFALs are relatively new production systems, so the optimum production technologies have not yet been established (Schueller, 2014) and there is much room for improvement in the plant production process. This chapter describes the state of the art regarding the plant production process, the floor plan of a PFAL, and sanitation issues. Sanitation is discussed in more detail in Chapter 24 from a different viewpoint. The procedures of seeding, seedling production, and transplanting are described in detail in Chapter 21. Data collection, analyses, visualization, diagnosis, and improvement methods for PFALs are described in Chapter 25.

19.2 Motion economy and PDCA cycle

To continuously improve operations in the plant production process, it is often useful to introduce the principles of motion economy and the PDCA (plan—do—check—act) cycle.

19.2.1 Principles of motion economy

For an existing PFAL, the manual operations in the production process need to be improved weekly or monthly to eliminate “muri” (overburden), “mura” (inconsistency), and “muda” (waste). This improvement process was invented and is being used by Toyota Motor Corporation, and is called “kaizen” (Kanawaty, 1992; Meyers and Stewart, 2002). In kaizen, motion economy and the PDCA cycle are an important concept and methodology.

The principles of motion economy form a set of rules and suggestions to improve the manual work in manufacturing and reduce fatigue and unnecessary movements by the worker, which can lead to a reduction in work-related trauma (http://en.wikipedia.org/wiki/Principles_of_motion_economy).

The principles of motion economy can be classified into three groups: (1) principles related to the use of the *human body*, (2) principles related to the arrangement of the *workplace*, and (3) principles related to the *design of tools and equipment*. These three principles are further divided into five to 10 steps (Wikipedia).

19.2.2 PDCA cycle

The PDCA cycle is a four-step model for carrying out change in any action process (Fig. 19.1). The PDCA cycle is repeated to continuously improve the process. In step 1 (plan), an opportunity is recognized and a change is planned. In step 2 (do), the change is tested and a small-scale study is carried out. In step 3 (check), the test is reviewed; the results are analyzed and what was learned is identified. In step 4 (act), action is taken based on what was learned in step 3. If the change did not work, the PDCA cycle is repeated with a different plan. If the change was successful, what was learned from the test is incorporated into wider changes and used to plan new improvements, thus beginning the PDCA cycle again.

19.3 Plant production process

A typical flow of operations in the plant production process focusing on the movement of plants is shown in Fig. 19.2. Panel, floor, and culture bed cleaning, etc. are not shown. Each step of the process is further broken down. Fig. 19.3 shows an example of the breakdown of step 1 (seeding for germination).

Currently, most handling operations in Fig. 19.2 are conducted manually if the daily production capacity of leaf greens is about 5000 heads (100 g/head) or less. If production capacity is over 10,000 heads/day, the following handling operations are semiautomated or automated in most cases: seeding, uploading, unloading, and transporting of culture panels to and from the tiers (see Chapter 21), weighing of leaf greens, packing the harvested produce in plastic bags, labeling the plastic bags containing leaf greens, packing the plastic bags into container boxes, labeling the container boxes, and wrapping the boxes before cooling. In the near future, the transplanting and transporting of boxes in the PFAL will be automated in large-scale PFALs. Operations that are difficult to fully automate include detecting and trimming damaged leaves and packing plastic bags into boxes.

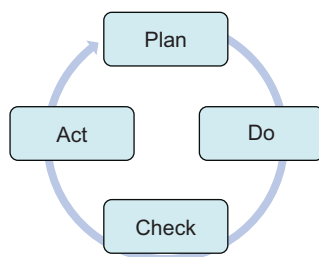
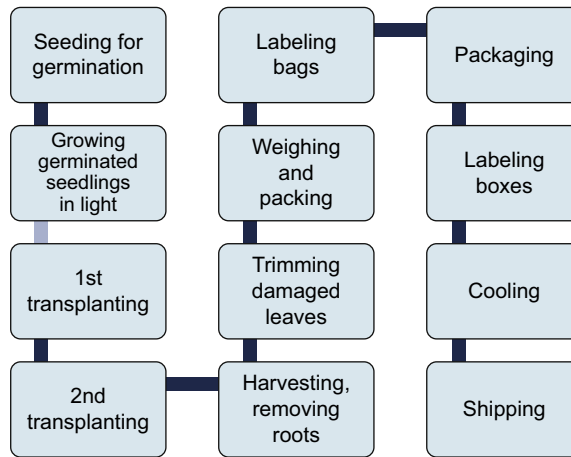
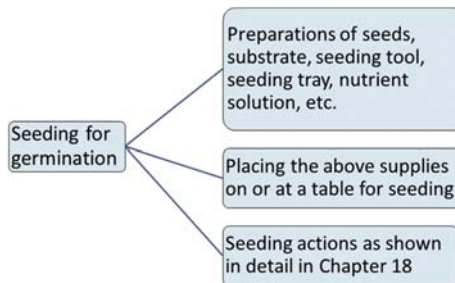


FIGURE 19.1

Scheme showing the PDCA (plan-do-check-act) cycle.

**FIGURE 19.2**

A typical flow of operations in the plant production process focusing on the movements of plants. Panel, floor, and culture bed cleaning, etc. are not shown.

**FIGURE 19.3**

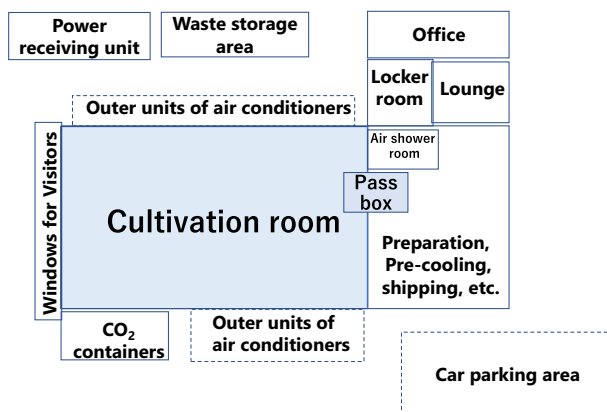
Breakdown of the first step (seeding for germination) of the plant production process shown in Fig. 19.2.

On the other hand, most manual operations in a PFAL are relatively simple, safe, and light work under a comfortable working environment (air temperature of 20–22°C), and so PFALs can create manual job opportunities suited to elderly and handicapped persons.

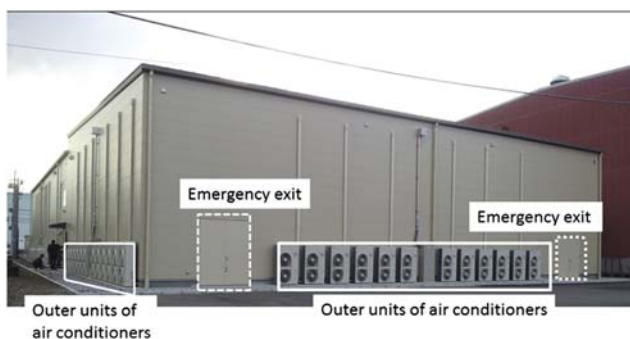
19.4 Layout

19.4.1 Floor plan

A rough floor plan of a PFAL is shown in Fig. 19.4. The PFAL consists mainly of an operation room and a cultivation room. The outer units of air conditioners are installed close to the walls outside (Fig. 19.5) and/or on the rooftop. Exposing an outer unit to direct solar light raises the temperature of its heat exchanger and increases the electricity cost for cooling, and thus should be avoided by shading.

**FIGURE 19.4**

Rough floor plan of a PFAL. Cultivation room is a sanitation area.

**FIGURE 19.5**

Outer units of air conditioners installed close to the building walls and emergency exits. The outer units can also be installed on the rooftop.

Photo courtesy of Mirai Co., Ltd.

The distance between the inner and outer units of air conditioners should be minimized to achieve a high coefficient of performance (COP) for cooling or electric energy efficiency of air conditioners for cooling. Accumulation of snow at the air inlet and outlet of outer units must be strictly avoided. When a PFAL is built in a cold region, air conditioners with special specifications must be chosen, which provide a high COP for cooling when the outside air temperature is 0°C or lower.

The position of the emergency exit is shown in Fig. 19.5. The door of the emergency exit needs to be thermally insulated to avoid water condensation on its inner surface and the surroundings in cool and cold seasons. Invasion by small insects and dust through air gaps around the door must be strictly prevented. The warehouse for garbage collection is placed at least 20 m away from the cultivation and operation rooms to discourage the movement of insects and small animals between the rooms and the warehouse.

The rest room, tea room, and administrative office are physically separated from the cultivation and operation rooms to maintain a high level of sanitation of these rooms, even though this is slightly inconvenient for workers. Since visitors cannot enter the operation and cultivation rooms, a corridor with glass windows through which they can look into the cultivation room may be provided.

19.4.2 Operation room

Fig. 19.6 shows a typical floor plan of the operation room. The installation of a hot water shower or air shower depends on the risk management policy of the PFAL operator. Hot water showers will lower the risk of biological contamination of the culture room, but take a much longer time to use than an air shower, so that air showers are recommended. Those intending to enter the operation room need to take an air shower before and after putting on clean clothing. Two separate air showers and changing rooms are provided for use by women and men, respectively. Those intending to enter the cultivation room through the operation room need to put on clean (disinfected) overalls, a head cap with a mask, a pair of gloves, and boots (Fig. 19.7), and then take an air shower again for 15–30 s before entering the cultivation room.

Supplies to be used in the cultivation room are transported through the pass box from the operation box. The air shower room and pass box in the operation room have doors at both sides to prevent the exchange of air between the operation and cultivation rooms. There is a glass window between the cultivation room and operation room, and video cameras can also be installed in both the operation and cultivation rooms. Work tables are movable. Supplies transported into the cultivation room through the operation room are sterilized in the UV sterilization box in the operation room.

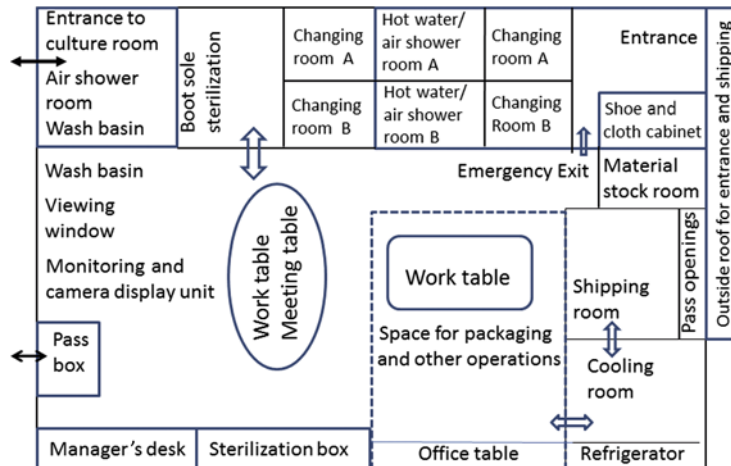


FIGURE 19.6

A typical floor layout of the operation room at a PFAL with a daily production capacity of 5000–10,000 lettuce heads. The cultivation room is located on the left-hand side. Floor areas of rooms and spaces are not shown to scale.

**FIGURE 19.7**

A worker wearing clean overalls. The cap, mask, and gloves are generally disposable. The overalls and boots are usually used again after washing and sterilizing.

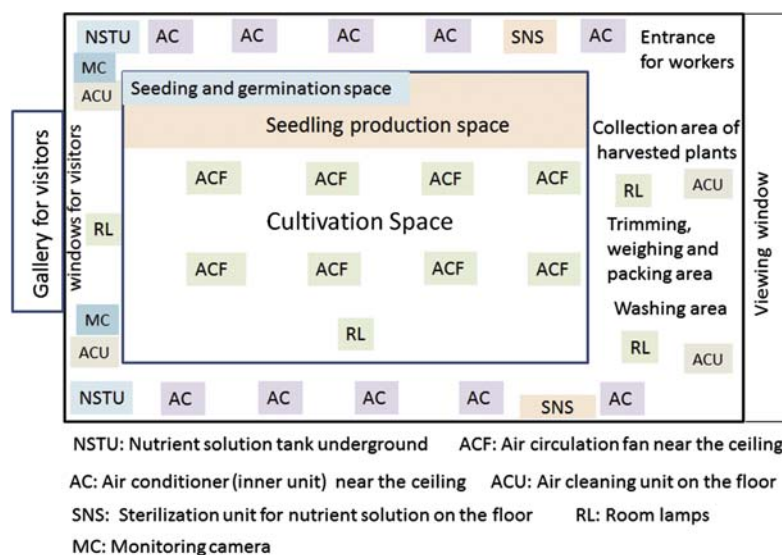
Photo courtesy of Mirai Co., Ltd.

Both the cultivation and operation rooms are clean, but the air in the cultivation room is cleaner than that in the operation room in terms of the population density of microorganisms (bacteria, fungi, and viruses). Thus, weighing, trimming of plants, packing of plants into plastic bags, and sealing of the plastic bags are conducted in the cultivation room, not in the operation room. After the plastic bags have been sealed, they are packed into the container boxes in the operation room, so the harvested produce packed and sealed in the cultivation room is cleaner [colony forming units (CFU)/g is lower] than that packed and sealed in the operation room. However, it should be noted that the population density of microorganisms in the cultivation beds can become very high if the beds are not sterilized often.

19.4.3 Cultivation room

The following steps are taken by workers entering the cultivation room: (1) enter the changing/locker room in the operation room, (2) take off all clothing except for underwear, (3) take an air shower for the whole body including hair/head cleaning, (4) put on clean (disinfected) overalls, cap, mask, and gloves, (5) wash the hands while wearing the gloves using a disinfectant for sterilization, (6) put on clean boots and sterilize the boot soles, (7) take an air shower again, and (8) enter the cultivation room. This procedure is similar to that for entering the micropropagation room for pathogen-free plants (Chun and Kozai, 2000).

Fig. 19.8 shows a typical layout of tiers with cultivation beds and equipment in the cultivation room. The cultivation area ratios of seeding, seedling production, and cultivation are roughly 1:12:50. Each shelf of the tiers is 1–2 m wide with an average of about 1.5 m. The tier length depends on the size of the cultivation room. The vertical distance between tiers is 30–100 cm with an average of around 50 cm. The walkway is 1 m wide on average but it largely depends on the method of transplanting and harvesting: (1) transplanting and harvesting are conducted at both ends of tiers and the

**FIGURE 19.8**

A typical floor layout of the cultivation room at a PFAL. Floor areas of rooms and spaces are not shown to scale. The cultivation space in the floor plan is a sanitary area.

walkway is used for maintenance, cleaning of cultivation beds, etc. only, or (2) transplanting and harvesting are conducted along the walkway. The walkway is narrower in the former case than the latter.

The directions of air outflow from the air conditioners and air circulation fans must be the same as those of the tiers. It is also important to move the room air vertically to obtain uniform vertical distributions of air temperature, VPD (vapor pressure deficit), air current speed, CO₂ concentration, and so forth.

Table 19.1 lists the equipment and sensors installed at fixed places in the culture room. In addition, there are movable carts with or without batteries for carrying culture panels, harvested produce, plant residue, packing boxes, and so forth. Also, there are movable lifts with or without batteries for uploading and unloading the culture panels with plants (Fig. 19.11).

In the design and construction of a highly airtight culture room, use of materials (panels for walls and floor, glue for piping, coolant for air conditioners) emitting volatile organic compounds (VOC) toxic to plants such as propylene glycol should be strictly avoided or minimized (Niu et al., 2005).

19.5 Sanitation control

19.5.1 Biological cleanness

The cultivation and operation rooms must be clean biologically as well as physically and chemically. In many industries, the cleanness of room air is expressed as the number of particles (physical objects)

Table 19.1 Equipment and environmental sensors typically installed at fixed places in the cultivation room.

Category	Equipment and environmental sensors
Electricity supply	Power distribution box, breakers, and relays
Air conditioning	Inner units of air conditioners with plumbing for refrigerant Plumbing for recycling use of drained water Air circulation fans Actual/set point temperature display unit Air cleaners with filters and ozone (O ₃) gas generator
Nutrient solution supply	Cultivation beds with circulation pumps Plumbing with strainers and valves Sterilization unit [filters, UV (ultraviolet) lamp, and O ₃ gas generator] (Fig. 19.9) Tank with a floating switch, and stock solution tanks Plumbing for civil or clean water supply, plumbing for drainage in emergency discharge
Lighting	Light source with reflectors Power stabilizer, inverters, and AC-DC converters
CO ₂ supply	Control unit with distribution tubes
Sanitation control	Washing/cleaning machine of cultivation panels (Fig. 19.10) Cleaning tools for floor and culture beds
Stock room	Supplies for plant production, sanitation, etc.
Sensors for environmental control	Air: temperature, relative humidity (VPD), CO ₂ concentration, and CO ₂ supply rate Nutrient solution: pH, EC (electric conductivity), temperature, water supply rate, and circulating nutrient solution flow rate Electrical energy: Watt meter, Watt-hour meter

with size of 0.1 (or 0.5) μm or larger per unit volume of air. Chemical cleanness of food is often expressed as the concentrations of heavy metals, agrochemicals, and other toxic chemical substances.

In a PFAL, biological cleanness of the room air, harvested produce, or nutrient solution is expressed as CFU (see Chapter 24), which is a measure of the population density of live microorganisms. It is generally considered that fresh vegetables can be eaten without washing if the CFU of the harvest is less than 300 per gram, while the CFU of field-grown lettuce heads ranges from 10,000 to 100,000 if not washed.

Microorganisms can be classified into four groups: (A) potentially harmful to humans but not to plants, (B) potentially harmful to plants but not to humans, (C) potentially harmful neither to humans nor to plants, and (D) potentially harmful to both humans and plants. Thus, in addition to CFU tests, weekly or monthly tests are necessary for measuring the population densities of harmful microorganisms such as the *Coliform* group and *Staphylococcus aureus* which may cause human disease (Chapter 24). These pathogens are often brought in by workers having symptoms of diarrhea, so these workers should not be allowed to enter the operation and cultivation rooms.

**FIGURE 19.9**

Sterilization unit with filters, UV lamp, and ozone generator for nutrient solution.

**FIGURE 19.10**

Culture panel cleaning machine.

Photo courtesy of Sashinami Seisakujo Corporation.

**FIGURE 19.11**

A lift with batteries for uploading and unloading the culture panels.

Photo courtesy of Hokuetsu Industries Co., Ltd.

In order to avoid the dispersion of pathogens that may cause diseases in plants, knives and scissors used for harvesting must be disinfected every time the workers harvest new culture beds or tiers. The propagation of microorganisms (fungi) such as *Pythium* spp. and *Fusarium oxysporum* Schlecht. f.sp. occurs mostly in the nutrient solution in the culture beds and wet surfaces where there is food for microorganisms.

In the nutrient solution in cultivation beds, there are many fine roots and algae (some dead and some alive) favored by microorganisms as food. Some microorganisms grow very rapidly under such favorable conditions, so the cultivation panels and cultivation beds must be cleaned by removing the fine roots, algae, and microorganisms every 2–4 weeks.

Continuous sterilization of recirculating nutrient solution is essential, although many microorganisms stay and propagate in the culture beds and do not move with the recirculating nutrient solution, while some pathogens in the nutrient solution move into the roots, propagate in the plants, and cause disease.

Typically, the population density of microorganisms is several hundred times higher in the nutrient solution than in the room air, so the following actions should be avoided: (1) dripping the nutrient solution onto the aerial part of plants, (2) dipping the aerial part of plants into the nutrient solution, (3) harvesting or touching the plants with gloves after touching the roots with gloves, and (4) leaving the roots on the floor, culture beds, and other places in the culture room.

19.5.2 ISO22000 and HACCP for food safety

There are two international standards for food safety control: ISO22000 and hazard analysis and critical control point (HACCP). The ISO22000 family of International Standards addresses food safety management. The ISO's food safety management standards help organizations identify and control food safety hazards. The ISO22000 family contains a number of standards, each focusing on different aspects of food safety management (http://en.wikipedia.org/wiki/ISO_22000).

HACCP is a system that helps food business operators assess how they handle food and introduces procedures to make sure the food produced is safe to eat. As of 2014, there are few PFALs producing vegetables under the ISO22000 and HACCP standards.

In Japan, the Third Party Accreditation Committee on Products and Product System (TPAC-PPS) was established in 2013 for evaluating products produced in PFALs in terms of pathogenic microorganisms, nutrient components for human health (vitamins A, B, C, etc.), toxic heavy metals, agrochemicals, and nutrient components for plants (NO_3^- , etc.). However, TPAC-PPS was not active as of 2018.

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Hydroponic systems

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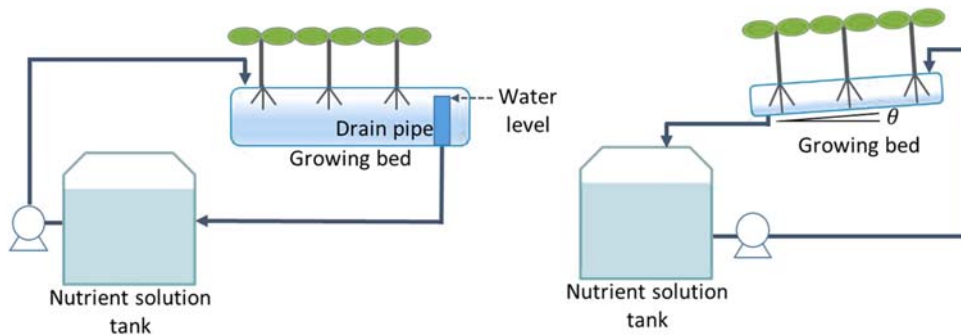
20.1 Introduction

Hydroponic systems are essential tools for plant production in indoor farming such as plant factories with artificial lighting (PFAL). Among various hydroponic systems, the deep flow technique (DFT), nutrient film technique (NFT), and aeroponic systems have been commercially used with recirculated nutrient solutions. Because ion concentrations in the nutrient solutions change with time causing a nutrient imbalance (Son and Takakura, 1987; Zekki et al., 1996; Cloutier et al., 1997), nutrient control systems with real-time measurements of all nutrients are required, but such systems are not yet available on a commercial basis. Instead, ion EC-based hydroponic systems have been the second-best choice but suffer from nutrient imbalance (Savvas and Manos, 1999; Ahn and Son, 2011). To improve the nutrient balance, periodical analysis of nutrient solutions and adjustment of nutrient ratios were conducted (Ko et al., 2013). As an advanced method, the ion-selective electrodes and artificial neural networks were used to estimate the concentration of each ion (Dorneanu et al., 2005; Gutierrez et al., 2007; Kim et al., 2013). To protect the plants in plant factories from disease, disinfection systems, such as ultraviolet (UV) systems, are required. The light intensity and exposure time of UV radiation are related with the disinfection ratio of pathogens (for example, Runia, 1995). This chapter describes the hydroponic systems, sensors and controllers, nutrient management systems, ion-specific nutrient management, and nutrient sterilization systems required for plant production in plant factories.

20.2 Hydroponic systems

A hydroponic system, or hydroponics, is a method of growing plants using mineral nutrient solutions in water without soil. For growing leafy vegetables in general, the main hydroponic systems used are the DFT and NFT systems. In the DFT system, nutrient solutions are supplied to the plants whenever the water level in the culture bed becomes lower than the set value, and are recirculated and supplied to the bare roots of plants, at constant time intervals, in the culture bed with a 1/100 slope. NFT systems and modified DFT systems similar to an ebb-and-flow system have been widely used in plant factories (Fig. 20.1).

In recirculation systems, nutrient solutions that are not absorbed by plants return to the nutrient tank. Therefore, water and nutrient absorption by plants can be easily estimated by measuring the loss

**FIGURE 20.1**

Schematic diagrams of DFT (left) and NFT (right) hydroponic systems.

of the nutrient solutions in the tank. In addition, aeroponic systems, which directly spray the nutrient solutions to the roots of the plants, also are used in plant factories.

20.3 Sensors and controllers

Root-zone environmental factors such as nutrient concentration, pH, dissolved oxygen, and temperature directly affect the growth of hydroponically grown plants. For real-time measurement of these factors, corresponding sensors are required. By assuming that the electric current increases with an increase of ionized nutrients in the nutrient solutions, electrical conductivity (EC) sensors are used to measure nutrient concentrations. Nutrient solutions absorbed by transpiration can be measured by water-level sensors in large nutrient solution tanks and by load cells in relatively small tanks. Ultrasonic wave or laser sensors can also be conveniently used for noncontact measurement of the water level in the tanks. The process of controlling the water and nutrient supplies is as follows: determine the amounts of stock nutrient solutions and water, inject them into the nutrient solution tank and mix them, and supply the mixed nutrient solutions to the plants. Nutrient control systems consisting of sensors and controllers are used commercially in hydroponic farms.

20.4 Nutrient management systems

20.4.1 Open and closed hydroponic systems

Hydroponic nutrient solutions are composed of 13 essential elements. Each nutrient has a suitable concentration and relative ratios for the normal growth of a plant, and these are the target values of a nutrient control system. However, ionic concentration in the nutrient solutions changes with time, and subsequently a nutrient imbalance occurs in the closed hydroponic system (Fig. 20.2).

Thus, in order to achieve optimal control, all nutrients should be measured in real time. However, such a system has both economic and technical limitations. High-precision instrument analysis is relatively expensive, and ion sensors are still at the research stage for their durability and stability. To date, the field application of real-time measurement systems for individual nutrients is difficult;

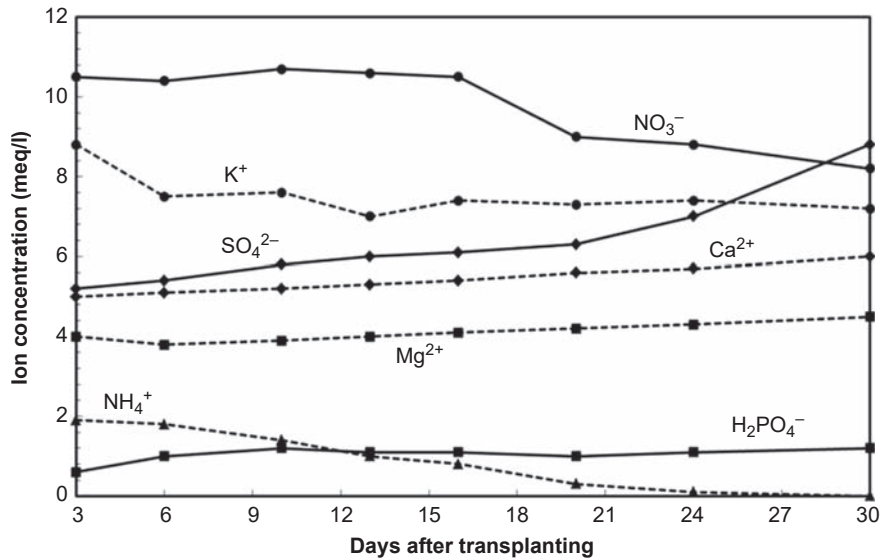


FIGURE 20.2

Changes in ionic concentration of the recirculated nutrient solutions controlled at a fixed EC (an example for lettuce).

instead, an EC and water-level sensor system for controlling total ion concentration is widely used. Closed systems that monitor the results of the control process are preferable for nutrient solution management (Fig. 20.3).

However, scaling-up the system requires a modular structure of the culture bed and drainage tank, and increasing the number of modules increases the installation cost. In contrast, open-loop control systems can have a relatively simple structure, even in the case of large-scale systems. But because they lack feedback, such systems might be inappropriate for plants which have higher fluctuations in uptake concentrations.

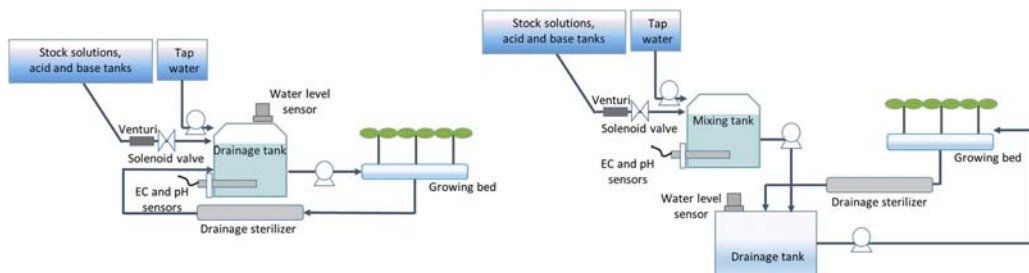


FIGURE 20.3

Schematic diagrams of closed (left) and open (right) hydroponic systems.

The concept behind EC-based hydroponic systems involves controlling total ion concentrations while minimizing nutrient imbalance through the injection of a stock solution. In order to operate the system normally, a theoretical understanding of the nutrient solution mixing procedure is required. The mixing process of nutrient solutions is discontinuously conducted by measuring changes in the amounts of nutrients and water in the drainage tank. This can be expressed as:

$$V_t EC_t = V_c EC_c + aU \quad U = \frac{V_t EC_t - V_c EC_c}{a} \quad (20.1)$$

where V_t is the target volume of the nutrient solution stored in the drainage tank; EC_t is the target EC value (dS m^{-1}); V_c and EC_c represent the current volume of nutrient solution and EC in the drainage tank, respectively; U is the total amount of nutrients absorbed by the plants in milli-equivalent; and a is the empirical coefficient for conversion of total salt concentration and EC. For hydroponic solutions, $a = 9.819$ was suggested as the value of the coefficient by Savvas and Adamidis (1999), which can be in the range of 0.8–4.0 dS m^{-1} . Based on Eq. (20.1), the required injection amount of stock solution can be calculated by:

$$V_t EC_t = V_c EC_c + V_w EC_w + V_{stk} EC_{stk} \quad V_{stk} = \frac{V_t EC_t - V_c EC_c - V_w EC_w}{EC_{stk}} \quad (20.2)$$

where V_w is the required injection amount of tap water; EC_w is EC of tap water; V_{stk} is the required injection amount of stock solution; and EC_{stk} is the conversion of the milli-equivalent concentration of stock solution to EC. The sum of V_c , V_w , and V_{stk} should be equal to V_t . Therefore, from this relationship, the following equation can be derived:

$$V_{stk} = \frac{V_t EC_t - V_c EC_c - EC_w (V_t - V_c)}{EC_{stk} - EC_w} \quad (20.3)$$

Once V_{stk} and V_w are calculated, these values are then submitted to the controller as reference input values, and actuators such as pumps and solenoids valves are activated.

20.4.2 Changes in nutrient balance under EC-based hydroponic systems

The transport of nutrients and water in the hydroponic system in Fig. 20.3 (left) can be expressed as a differential equation. Silberbush et al. (2001) constructed this model, and the above-mentioned EC-based nutrient solution mixing process is applicable in the model. The following equations are simplified models of nutrient and water transport in EC-based hydroponic systems.

$$V_b \frac{dC_b^i}{dt} = Q_{ir} C_{drg}^i - \frac{V_{max} C_b^i}{K_m + C_b^i} - (Q_{ir} - Q_{trs}) C_b^i \quad (20.4)$$

$$V_{drg} \frac{dC_{drg}^i}{dt} = (Q_{ir} - Q_{trs}) C_b^i + Q_{inj} C_{inj}^i + Q_{wtr} C_{wtr}^i - Q_{ir} C_{drg}^i \quad (20.5)$$

$$\frac{dV_b}{dt} = Q_{ir} - Q_{trs} - (Q_{ir} - Q_{trs}) \quad (20.6)$$

$$\frac{dV_{drg}}{dt} = (Q_{ir} - Q_{trs}) + Q_{inj} + Q_{wtr} - Q_{ir} \quad (20.7)$$

where V_b is the volume of the nutrient solution in the culture bed; V_{drg} is the stored nutrient solution in the drainage tank; C represents the concentration of individual nutrients, superscripts indicate the names of nutrients, and subscripts indicate the position of the nutrients; Q_{ir} is the irrigation rate; Q_{trs} is the transpiration rate; Q_{inj} is the stock solution injection rate; and Q_{wtr} is the tap water injection rate. Q_{inj} and Q_{wtr} are calculated by the above equation, and V_{max} and K_m are coefficients for Michaelis–Menten kinetics.

Based on this model, changes in nutrient concentration and balance under EC-based hydroponic systems can be simulated. Fig. 20.4 shows the simulated results of the changes in the concentrations and ratios of K^+ , Ca^{2+} , Mg^{2+} , and Na^+ . In practice, the absorption ratios between nutrients are not equal to the ratios in the nutrient solution, and therefore changes in the nutrient balance are observed during cultivation periods. The simulated results adequately show these tendencies. Nutrients which have relatively lower absorption rates such as Na^+ gradually increase in the nutrient solution. In EC-based hydroponic systems, the total ion concentration in the drainage tank is fixed at a target value; thus, it limits the injection amount of the stock solution. Therefore, the nutrient ratio of Na^+ in the nutrient solution rapidly increases, and this can result in a decrease of injection of other nutrients from the stock solution and lead to the development of salinity stress. However, if the tap water Na^+ concentration is in a certain range, the dynamic equilibrium can then be observed (Savvas et al., 2008). A major source of Na^+ inflow is tap water; therefore, the concentration at equilibrium is decided by the concentration in the tap water, the transpiration rate, and the absorption rate. If the predicted equilibrium concentration is above the threshold of a cultivated plant, then the application of a desalinator needs to be considered. Furthermore, ratios of other essential nutrients are important for normal plant growth, thus it is necessary to periodically analyze the nutrient solutions and adjust the nutrient ratios in the stock solution before deficiency or toxicity develops (Ko et al., 2013).

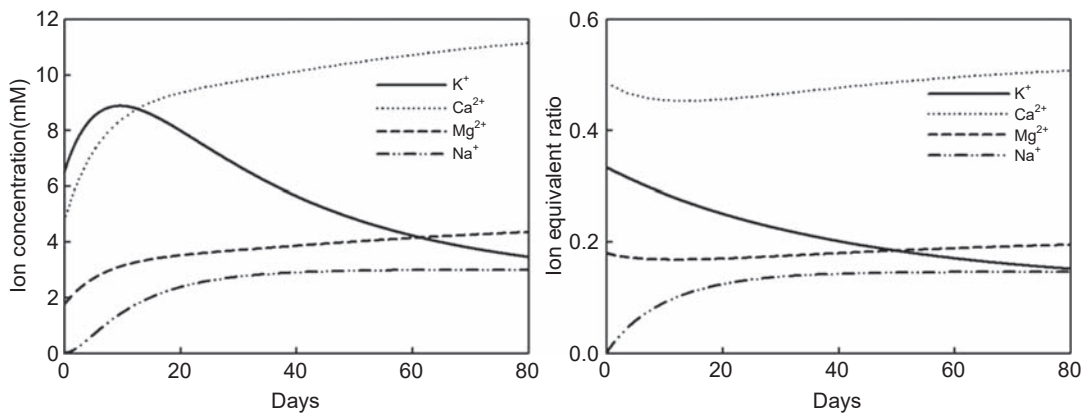


FIGURE 20.4

Simulated changes in the ion concentration (left) and the ion equivalent ratio (right) in the culture bed under an EC-based nutrient management system.

20.5 Ion-specific nutrient management

Hydroponic solutions contain various nutrients essential for crop growth. These nutrients are generally taken into plants in various ionic forms, such as NO_3^- , H_2PO_4^- , or HPO_4^{2-} , and K^+ through a combination of root interception and diffusion. Since the reserves of nutrients for the plants are limited in hydroponic greenhouse cultivation, an inaccurately balanced nutrient solution may result in an unbalanced nutrient composition in the root environment. In particular, deviations from the optimal concentration of any one ion can lead to the development of toxicity or deficiency symptoms and ultimately impair productivity (Bamsey et al., 2012).

In closed hydroponic systems that reuse the drainage solution, the build-up of salts is managed by dramatically reducing the fertilizers that are dissolved in the water, which are added to replenish the drainage solution (Fig. 20.5). However, in closed systems such as NFT, DFT, and ebb-flow systems, it is important to determine the nutrient concentrations in the reused solution to regenerate a nutrient solution of optimal composition because prolonged reuse of drainage water may lead to an accumulation of some nutrients, resulting in alterations in the nutrient ratios (Gutierrez et al., 2007).

To overcome such limitations regarding the use of closed systems on a practical scale, a feedback control loop that uses an ion analyzer is needed to dilute liquid fertilizers on the basis of on-line measurements of nutrient concentrations (Gieling et al., 2005). In addition, an algorithm implemented in a computer program is used to generate the time duration values needed to activate the valves for the addition of liquid fertilizer by the injection unit (Savvas and Manos, 1999). Current practices for managing hydroponic nutrients in closed systems are usually based on automatic control

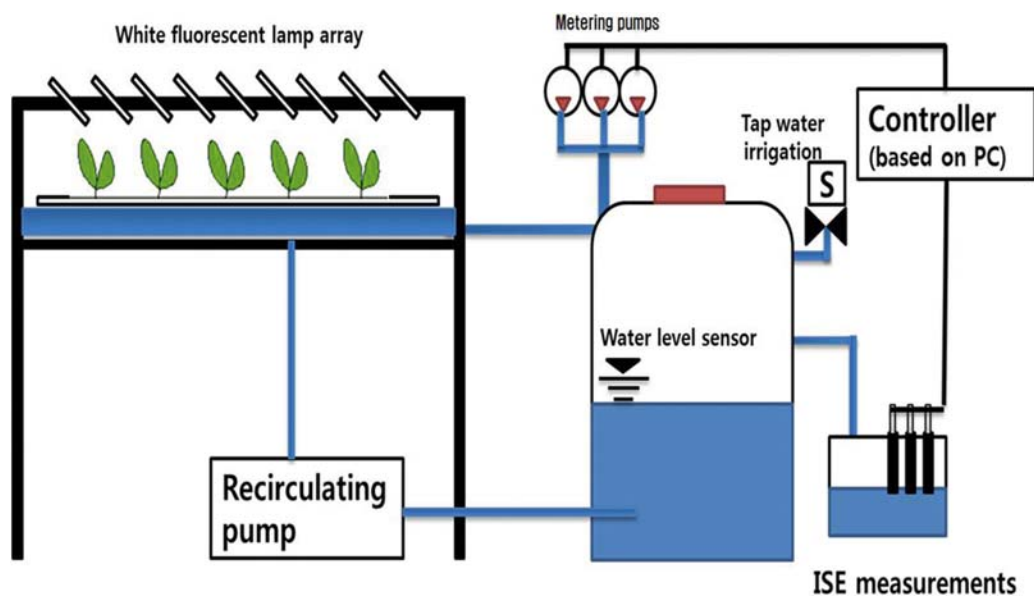


FIGURE 20.5

A schematic diagram of a closed hydroponic system based on nutrient feedback control.

of EC in the nutrient solution. A main problem with this practice is that EC measurements provide no information on the concentrations of individual ions and therefore do not allow individual real-time corrections to be made to each nutrient in response to the demand of the crop (Cloutier et al., 1997). Improved efficiency of fertilizer utilization may be possible through accurate measurement and control of the individual nutrients in the solution in real time.

The need for such fast, continuous monitoring has led to the application of ion-selective electrode (ISE) technology to measure hydroponic nutrients (Cloutier et al., 1997; Gutierrez et al., 2007). The advantages over standard analytical methods (spectroscopic techniques) include simple methodology, direct measurement, sensitivity over a wide concentration range, low cost, and portability (Heinen and Harmanny, 1992; Kim et al., 2013). The key component of an ISE is the ion-selective membrane that responds selectively to one ion in the presence of other ions in a solution. There are currently ion-selective membranes available for most of the important hydroponic nutrients, including NO_3^- , K^+ , Ca^{2+} , and NH_4^+ . However, there are several potential disadvantages of ion-selective electrodes as compared to standard analytical methods. One is chemical interference by other ions because ion-selective electrodes are not truly specific but rather respond more or less to a variety of interfering ions. To overcome interference issues, various data-processing methods such as multivariate calibration and artificial neural network (ANN) methods can be used. The multivariate calibration method is useful for allowing the cross responses arising from primary and interfering ions for accurately determining individual ion concentrations (Forster et al., 1991). An ANN method that uses data obtained with an array of multiple electrodes can be used for the simultaneous determination of various ions (Gutierrez et al., 2007). For example, as shown in Fig. 20.6, in a previous study that determined NH_4^+ , K^+ , Na^+ , and NO_3^- ions in a hydroponic solution, the ANN was able to predict the concentrations of the tested ions with an acceptable level for almost 3 days without the need to remove the interfering effects.

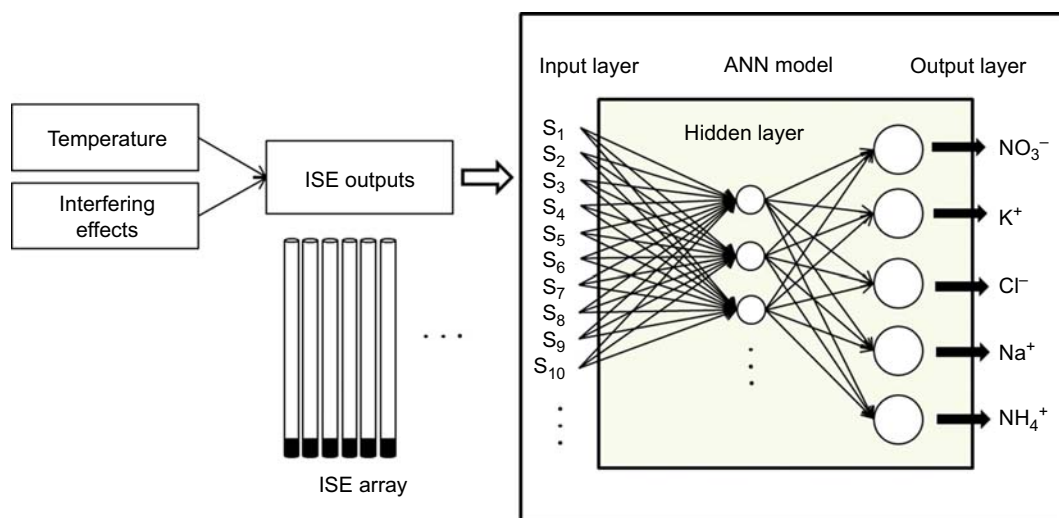


FIGURE 20.6

A schematic representation of the ANN method using an array of ion-selective electrodes.

Another disadvantage is reduced accuracy due to electrode response drift and biofilm accumulation caused by the presence of organic materials in hydroponic solutions (Carey and Riggan, 1994; Cloutier et al., 1997). In particular, stability and repeatability of the sensor response may be a major concern when considering an in-line management system that includes continuous immersion of ISEs in hydroponic solution because the accuracy of the measurement may be limited by the drift in electrode potential over time. The use of a computer-based automatic measurement system would improve the accuracy and precision of determining nutrient concentrations because consistent control of sample preparation, sensor calibration, and data collection can reduce variability among multiple electrodes during replicate measurements (Dorneanu et al., 2005; Kim et al., 2013). Ideally, an automated sensing system for hydroponic nutrients would be able to periodically calibrate and rinse the electrodes and continuously measure the nutrients in the hydroponic solution while automatically introducing solutions for calibration and rinsing as well as measurement. For example, in a previous study (Cho et al., 2018), a prototype of an on-site ion-monitoring system was developed to automatically measure the concentrations of three individual ions, i.e., NO_3^- , K^+ , and Ca^{2+} , in hydroponic solutions (Fig. 20.7).

In closed soilless culture systems, the nutrient solution is usually prepared by fertilizer injection systems consisting of pumps and valves (Jung et al., 2015). The ratios are generally regulated by dispensing stock solutions according to real-time measurement of EC or nutrient concentrations to effectively achieve a preset value (Gielsing et al., 2005; Savvas and Manos, 1999). A computer algorithm is used to calculate the amounts of stock solutions to be supplied and determine the time durations to activate the solenoid valves for the addition of fertilizers by the injection unit. The volumes of the nutrient stock solutions can be calculated simultaneously using a matrix equation (Jung et al., 2015) or separate calculations of the amounts of the individual nutrients to be replenished can be performed according to specific ions in a sequential order (Cho et al., 2017).

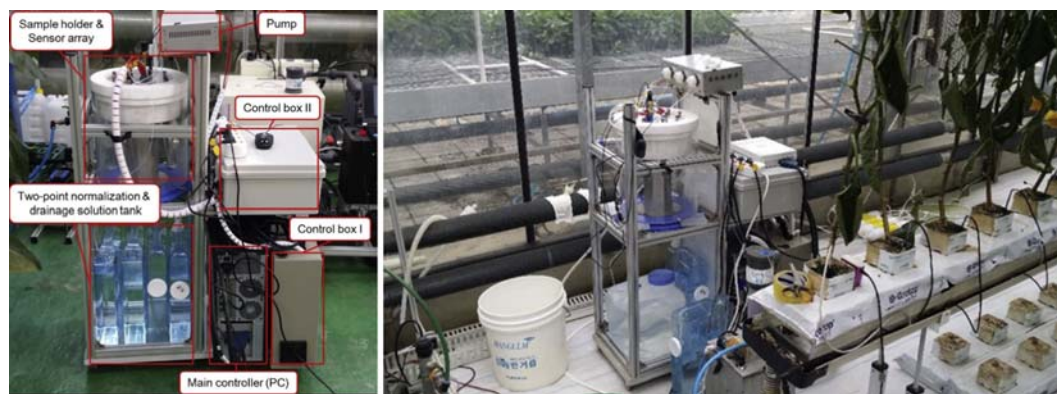


FIGURE 20.7

The hardware components of the prototype on-site ion-monitoring system (left) and a view of a greenhouse with the on-site ion monitoring system that monitors changes in hydroponic nutrients for paprika (right).

20.6 Sterilization systems

In general, contamination of crops by pathogens is lower in hydroponic cultures than in soil cultures; however, the pathogens can quickly spread to neighboring plants through the nutrient solutions when even one plant is contaminated. In order to minimize this risk, disinfection systems using filters, heat, ozone, and UV radiation are used in hydroponics.

Filtering systems eliminate the pathogens and other soluble solids in the nutrient solution, and their capacity is determined by pore size. Heating systems sterilize the pathogens by heating the nutrient solutions. Because the temperature for sterilization differs depending on the pathogen species, adequate ranges of temperatures should be set. After the heating treatment, a cooling process is required for reuse of the nutrient solutions on crops. Ozone (O_3) systems sterilize the nutrient solutions by using the oxidizing capacity of ozone gas. UV systems have the advantage of fast sterilization of pathogens in the nutrient solutions passing through the tube of the sterilizer. A light intensity of at least 250 mJ cm^{-2} is required to disinfect the pathogens perfectly (Runia, 1995). Even though the light intensity is within an adequate range, the sterilizing capacity decreases due to a lower transmittance of UV radiation if the turbidity of the nutrient solutions increases. To prevent this, filters should be installed in front of the UV sterilizer (Fig. 20.8). A disadvantage of UV systems is that the Fe-EDTA (chelating agent, ethylenediaminetetraacetic acid) in the nutrient solutions is precipitated and cannot be used. Therefore, addition of Fe-EDTA is required to compensate for the loss of Fe in hydroponic systems.

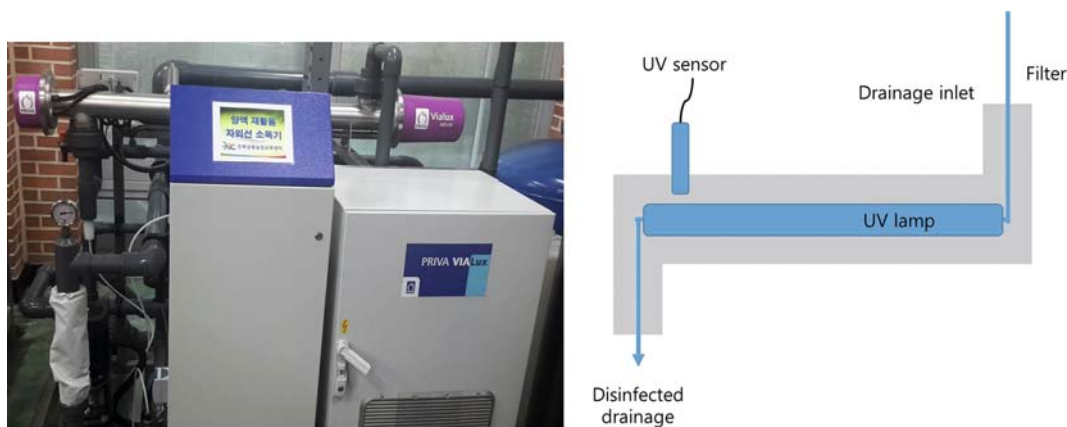


FIGURE 20.8

Commercial UV sterilizer (left, from the catalog of Priva) and schematic diagram of the structure (right).

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Seeding, seedling production and transplanting

21

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21.1 Introduction

A standard procedure for producing seedlings in a plant factory with artificial lighting (PFAL), consisting of preparation, seeding, seedling production, and transplanting, is described in this chapter. The procedure described here needs to be modified depending on the plant species, culture system, daily production capacity of the PFAL, etc. The numerical values given in the description are merely examples and should be modified to suit the particular situation. Leaf lettuce (*Lactuca sativa* L. var. *crispa*) is chosen as the plant material in this chapter.

The objective of this chapter is to provide the standard procedure for achieving a percent seed germination of 99% or higher (the percentage achieved by beginners would be around 90%), and percent transplantable seedlings from germinated seeds exceeding 99%. Accordingly, the percent transplantable seedlings from seeds sown exceeds 98% ($= 99 \times 99/100$) or higher. The percent salable harvests of seeds sown and of transplanted seedlings should exceed, respectively, 98% or higher and 99%.

21.2 Preparation

- (1) Choose either untreated or treated seeds (Fig. 21.1). Treated seeds include naked (shell-less) and coated seeds. Treated seeds for enhancing rapid and uniform germination are preferable to untreated seeds.
- (2) Caution is necessary regarding whether or not to treat the seeds with a fungicide. The choice depends on the purpose of seedling production and the biological characteristics of the seeds.
- (3) Eliminate low-quality seeds based on their size, shape, color, and (specific) weight through visual checking or by using an automatic grading/sorting machine.
- (4) Prepare a sponge-like or foamed urethane seeding mat (called “mat” hereafter) ($28 \times 58 \times 2.8$ cm) (Fig. 21.2) consisting of 300 cubes or cuboids ($2.3 \times 2.3 \times 2.8$ cm) each with a small hole (7–10 mm in diameter, 5–10 mm in depth) on the upper surface of the cube. Each cube can be separated easily by hand from the mat (Fig. 21.3).



FIGURE 21.1

Lettuce seeds untreated (left) and coated (right). Treated seeds are classified into naked (shell-less) seeds, coated seeds, and coated naked seeds.

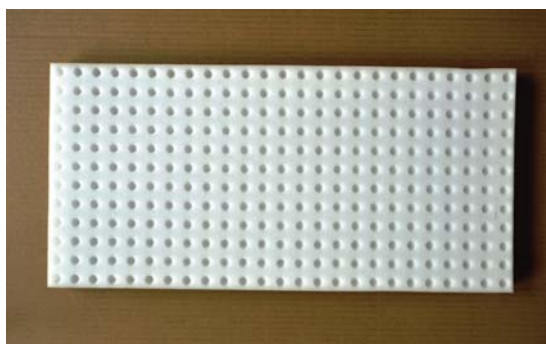


FIGURE 21.2

White-colored seeding mat (sponge-like foamed urethane mat) (28 cm wide, 58 cm long, and 2.8 cm high) consisting of 300 cuboids ($2.3 \times 2.3 \times 2.8$ cm).

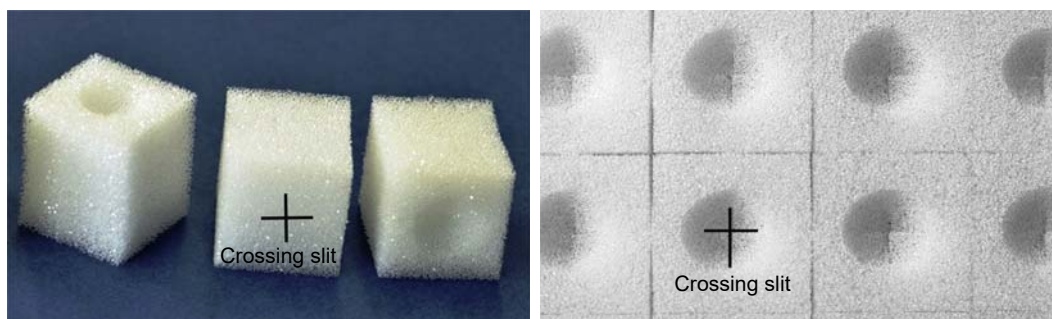


FIGURE 21.3

The cuboids each with a hollow at the center of the upper surface. There is a crossing slit at the center of each hollow to encourage the radicle of the germinated seed to grow downward smoothly.

- (5) At the center of each hole, there is a crossing slit (each 10 mm long) reaching the bottom of the cube to encourage the radicle (the youngest primary root) of a germinated seed to grow downward easily.
- (6) Prepare a foamed plastic tray (outside dimensions: 30 × 60 × 4.0 cm) to hold the mat (Fig. 21.4). Measure the weight of the empty tray prior to putting the mat in the tray.
- (7) Prepare a predetermined volume (3 L per tray) of nutrient solution, the strength of which is 1/4–1/8th that of the nutrient solution to be used after the second transplanting.
- (8) Press down the mat surface uniformly using a flat plate (30 × 60 cm) with many small holes or a press machine (Fig. 21.5) with a stacking and automatic feeding unit to drive out all the air from the mat. This step can be conducted by hand if only a few mats are to be pressed.



FIGURE 21.4

Formed, foamed polystyrene tray (relatively hard) to store the seeding mat (outer dimensions: 30 cm wide, 60 cm long, and 4 cm high; inner dimensions: 28 cm wide, 58 cm long, and 2.8 cm high).



FIGURE 21.5

A press machine for foamed mats to drive out all the air from the mat and fill the pores with water. The machine can be connected to a stacking and automatic feeding unit.

Sasinami Seisakujo Corporation, Aichi Prefecture, Japan.

- (9) Concurrently, soak the mat in nutrient solution so that all the capillary tubes and/or pores in the mat are filled with nutrient solution, resulting in no air bubbles in the mat.
- (10) Weigh the tray containing the mat and nutrient solution, and add or remove a small amount (ca. 0.2 L) of nutrient solution to obtain the predetermined target weight of 3280 g (e.g., 215 g for tray, 3000 g for nutrient solution, and 65 g for the mat) common to all the trays.
- (11) Check that the surface of the horizontal mat is wet evenly and that the level of free nutrient solution is just at the bottom of each hole of the mat. An evenly wet mat surface and free nutrient solution at the bottom of holes are important to achieve uniform seed germination over the mat. If the wetness at the mat surface is uneven, often due to insufficient capillary suction within the mat, the mat needs to be replaced with a new one.

21.3 Seeding

- (12) Place one seed in the wet hole of each cube (Fig. 21.6) using tweezers, a seeding plate, a semiautomatic seeder (Fig. 21.7), or an automatic seeding machine (Fig. 21.8). Confirm that the seed touches the wet center of the hole.
- (13) Cover the mat surface with thin plastic film (0.02 mm thick) to keep its surface constantly moist during the germination stage (Fig. 21.9).
- (14) Move the trays to a germination space. Ensure that the trays are always horizontal to prevent the seeds and nutrient solution from moving in the tray during transportation.
- (15) The trays are stacked in case the seeds are negatively photoblastic (dim light is unnecessary for germination of photoblastic seeds). Apply a slight downward pressure on the mat surface of the uppermost tray using an additional thin plastic plate (0.5–1.0 mm thick).
- (16) If the seeds are positively photoblastic, the trays are placed in a germination rack with the vertical distance between the tiers being 7–10 cm. Dim light is applied to the surface of each mat from the side using vertically placed fluorescent tubes or string-type LED lamps.

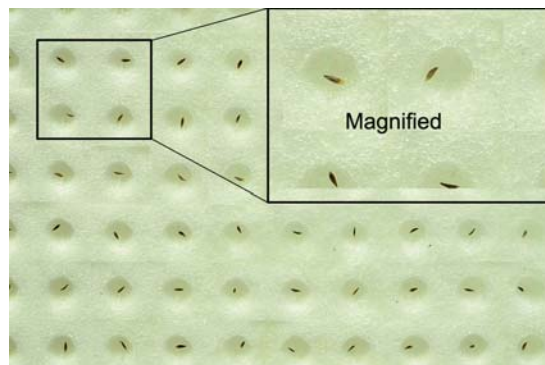


FIGURE 21.6

Lettuce seeds sown on the mat. The seeds touch the wet center of the hole to germinate smoothly.



FIGURE 21.7

Tweezers (upper left), seeding plate (lower left), and semiautomatic seeding tool (right: Minoru Industrial Co., Ltd., Okayama Prefecture, Japan). The seeding plate has two transparent plastic plates with small holes in a grid-like fashion. A handle is connected to the right-hand side of the upper plate. When one seed has been placed in each hole of the upper plate, the seeding plate is placed above the mat and the handle is pulled to the right-hand side. Then, each seed falls down at each center of the hole. The seeds are stacked in the upper container of the semiautomatic seeding tool. The machine is moved to the left-hand side manually. Then, one seed drops down from a hole at the bottom of the rotary container. The distance between the holes can be adjusted manually to suit different mats.

**FIGURE 21.8**

Automatic seeding machine for sponge-like seeding mat.

Nansei-Kobashi Co., Ltd., Mie Prefecture, Japan.

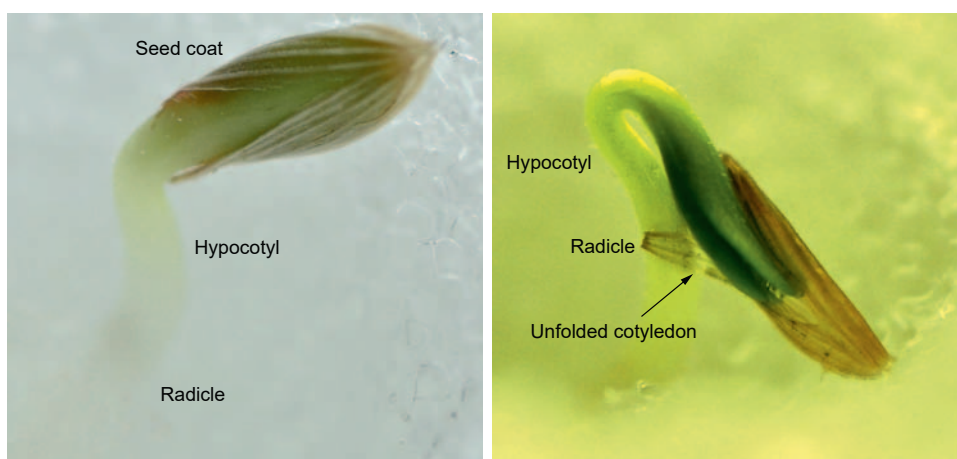
**FIGURE 21.9**

Formed polystyrene tray with seeds covered with thin plastic film (0.02 mm thick) (left) and covered with an empty foamed polystyrene tray (right) to keep the mat surface wet.

- (17) Microorganisms grow easily in the germination space, so periodic cleaning and/or sterilization are required.
- (18) The set point of air temperature varies between 15°C and 30°C with the plant species and cultivar (15–22°C for lettuce plants).
- (19) Two to 3 days after sowing, remove the plastic film from the tray.
- (20) At seed germination, a radicle comes out first (Fig. 21.10). Then, the hypocotyl with unfolded cotyledon leaves covered with seed coat appears (Fig. 21.11).
- (21) Confirm that all the radicles are growing downward into the mat. By applying slight downward pressure to the germinating seeds, the radicles grow downward smoothly through the crossing slit into the bottom of the cube. If the downward pressure is too low, the radicle will not penetrate the mat (Fig. 21.12).

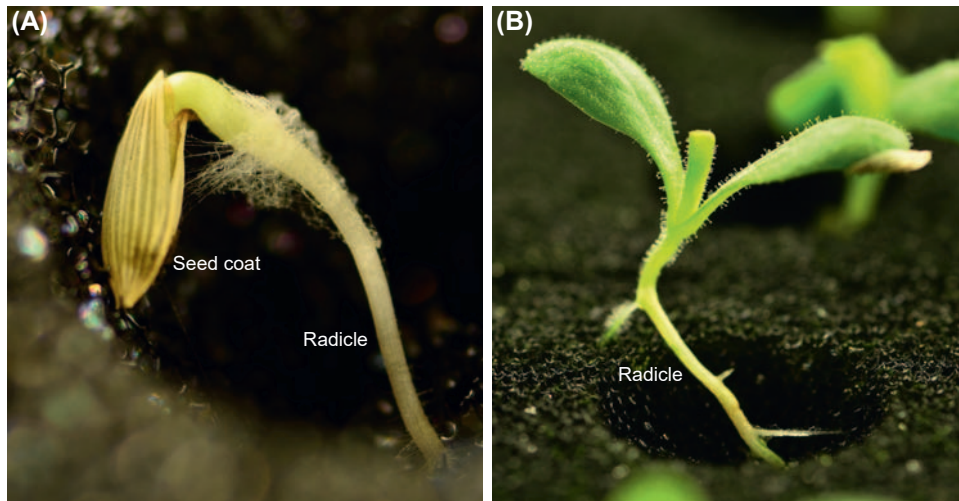
**FIGURE 21.10**

Germinated lettuce seed with radicle. Hypocotyl and cotyledon are still in the seed coat.

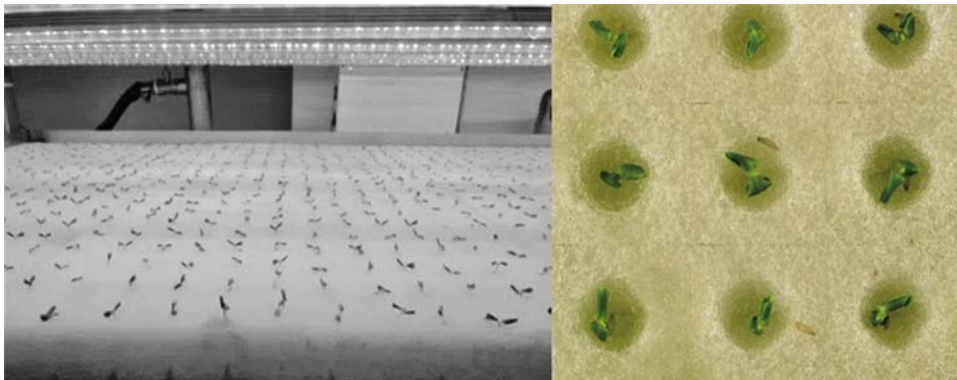
**FIGURE 21.11**

Lettuce (*Lactuca sativa* L. var. *crispa*) seed 22 h after seeding (left) and 42 h after seeding (right). Cotyledon is still folded and partly in the seed coat.

- (22) At this stage, percent germination is expected to be 99% or higher. If not, it is necessary to analyze the cause to improve the percent germination.
- (23) Move the trays from the germination space to a seedling production space. Hereafter, the seedlings grow by photosynthesis.
- (24) Grow the germinated seeds to seedlings with unfolded green cotyledons at a photosynthetic photon flux density (PPFD) of about $50\text{--}100\ \mu\text{mol m}^{-2}\text{s}^{-1}$. Green cotyledons usually expand fully in 4–7 days after seeding (4 days in the case of lettuce seeds) (Figs. 21.13 and 21.14).

**FIGURE 21.12**

Germinated lettuce seed with radicle which did not penetrate into the substrate. The radicle was lifted up from the substrate, (A) 2 days after seeding, and (B) 7 days after seeding.

**FIGURE 21.13**

Lettuce (*Lactuca sativa* L. var. *crispa*) seeds with cotyledons 72 h after seeding. The cotyledon is nearly unfolded and starts photosynthetic activity at this growth stage.

- (25) Algae grow quickly on the wet mat surface under light (Fig. 21.15). To prevent this, the level of free nutrient solution in the tray needs to be lowered by 10 mm to keep the mat surface dry, when the radicle with fine roots or rootlets comes out into the nutrient solution (Fig. 21.16).
- (26) A black-colored sponge-like, foamed urethane seeding mat is effective to suppress algae growth, although PPFD is reduced due to its low light reflectivity (Fig. 21.17).

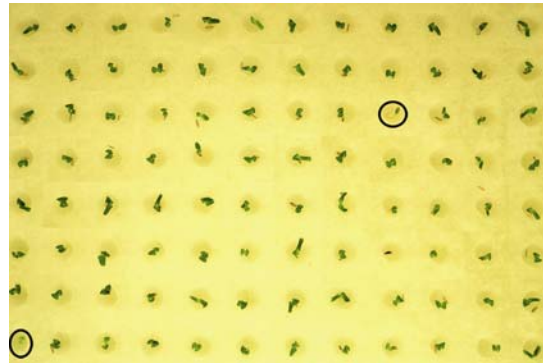


FIGURE 21.14

Ninety-six germinated lettuce seeds on the foamed urethane mat, 5 days after seeding. For commercial plant production, the germination percentage needs to be 98% or higher. In the photograph, the two seeds in the circle germinated 2 days later than the other seeds.

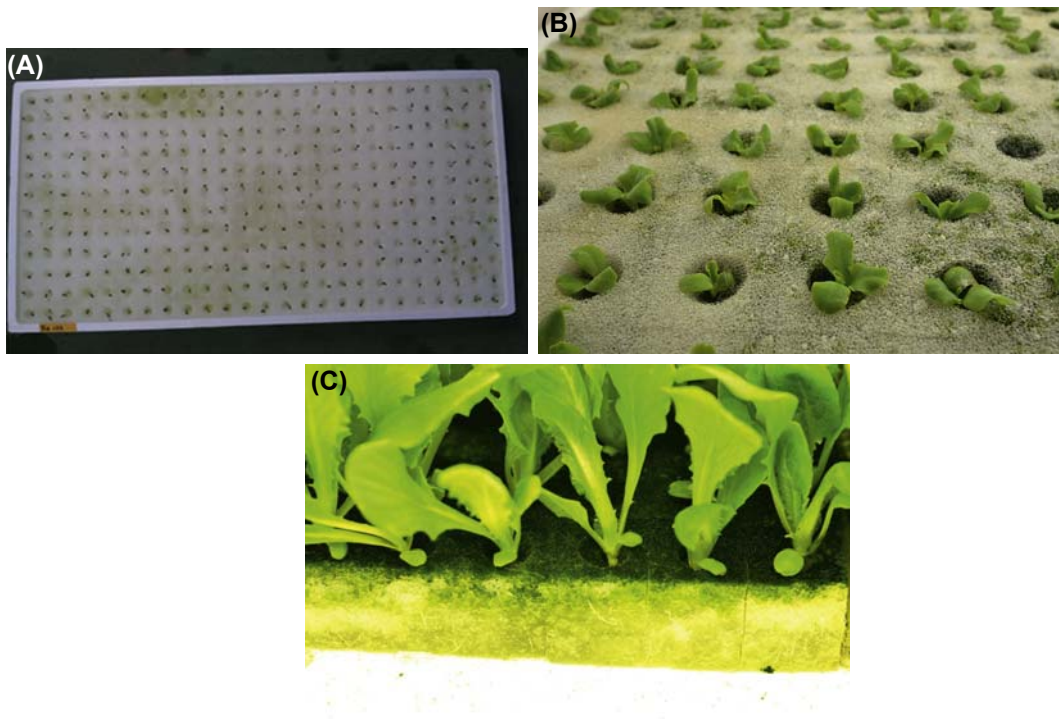
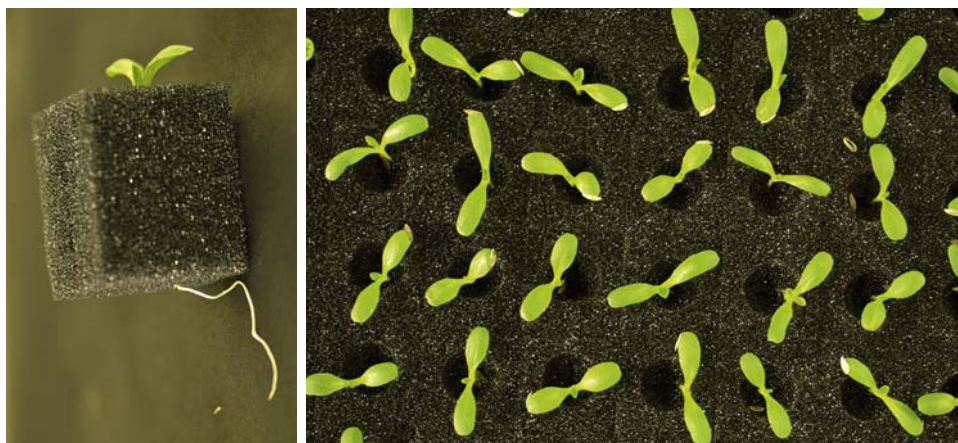


FIGURE 21.15

Algae grow quickly in the presence of light and nutrient solution on the wet seeding mat surface. (A) Spotted algae growth on the mat; (B) spotted algae growth on the mat; (C) algae growth on the surface and within the mat.

**FIGURE 21.16**

Seedling with roots which penetrated the cuboid. At this timing, the level of nutrient solution is lowered by 10 mm to allow the seedling mat surface to dry out and thus inhibit rapid growth of algae.

**FIGURE 21.17**

Black-colored seeding mat (sponge-like foamed urethane mat) which suppresses the growth of algae.

21.4 Seedling production and transplanting

- (27) Three to 7 days after seeding, cotyledons are unfolded and green in color. In the case of lettuce seeds, cotyledons are fully unfolded 72 h after seeding. Then, small true leaves can be observed by 5 days after seeding. Seven days after seeding, two true leaves are unfolded (Fig. 21.18).
- (28) The seedlings start growing quickly 10–12 days after seeding. The seedlings 14–16 days after seeding (Fig. 21.19) are suitable for the first transplanting to a culture panel (30 × 60 × 1 cm) having 24–30 holes (Fig. 21.20)
- (29) Transplant each seedling with the cube to the culture panel for further growth after the radicle with rootlets has come out from the bottom surface of the cube and the radicle is submerged

**FIGURE 21.18**

Lettuce seedlings with unfolded cotyledon 3 days (upper left), 5 days (upper right), and 7 days (bottom) after seeding.

**FIGURE 21.19**

Lettuce (*Lactuca sativa* L. var. *crispa*) seedlings 14 days after seeding, ready for the first transplanting. Black-colored foamed urethane cubes are used as substrate.

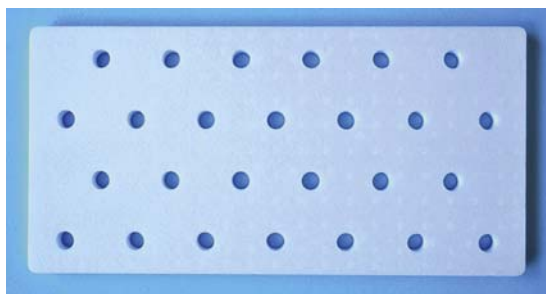


FIGURE 21.20

Formed culture panel (relatively hard board) with 26 holes (2.2 cm in diameter) for the first transplanting (29.8 cm wide, 59.6 cm long, 1.4 cm thick).



FIGURE 21.21

Lettuce seedlings (*Lactuca sativa* L. var. *crispa*) 24 days after seeding, ready for the second transplanting. Fresh weight: 10–12 g/plant, root fresh weight ratio: 0.40–0.45.



FIGURE 21.22

Formed culture panel (relatively hard board) with six holes (2.2 cm in diameter) for the second transplanting (29.8 cm wide, 59.6 cm long, 1.4 cm thick).

about 30 mm beneath the bottom surface. Transplanting can be done manually or using a transplanting machine.

- (30) Twelve (= 300/25) culture panels (formed, foamed urethane board) each with 26 holes (Fig. 21.20) or 10 (= 300/30) culture panels with 30 holes are necessary for each mat having 300 cubes.
- (31) The culture panel with 25–30 seedlings is placed in a hydroponic system with a culture bed and nutrient solution circulation unit to grow the seedlings further at a PPFD of $100\text{--}150\ \mu\text{mol m}^{-2}\text{ s}^{-1}$ for about 10–15 days to obtain larger seedlings ready for the second transplanting (Fig. 21.21), when the ratio of projected leaf area to the culture panel area exceeds 0.9.
- (32) The second transplanting is conducted using a culture panel (formed, foamed urethane board) with six to eight holes (Fig. 21.22). The larger the seedlings, the harder it is to pick them up and transplant them. However, the total cultivation area required for seeding, seedling production, and cultivation after the second transplanting can be reduced if larger seedlings are used for the second transplanting.
- (33) If the hypocotyl of a transplant is too elongated, the transplant tends to lie down on the culture panel and its growth is delayed for a few days.
- (34) The growth after the second transplanting is enhanced when the CO_2 concentration is increased up to around 1000 ppm.

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Transplant production in closed systems

22

22.1 Introduction

The closed transplant production system (CTPS) is a type of plant factory with artificial lighting (PFAL) or closed plant production system (CPPS) that is designed and operated specifically for the production of transplants (seedlings including grafted seedlings from seeds, and plantlets from cuttings/explants) (Kozai et al., 2004). The CTPS is used also for the acclimatization of micropropagated plantlets and for the vegetative propagation (multiplication) of plants (Chun and Kozai, 2000).

The CTPS is useful for producing transplants with desirable ecophysiological characteristics by environmental control (Kozai, 2007). Examples include: (1) tomato seedlings with flower buds at the eighth node or lower which enable early first harvesting and thus higher annual yield, (2) seedlings with thick and short hypocotyl (stem), which are resistant to environmental stresses including high winds and heavy rain, (3) seedlings with soft and elongated hypocotyl, which are necessary for easy cutting of hypocotyl by hand or a cutting machine to produce scions or root stocks for grafted seedlings, and (4) transplants that are physiologically and morphologically uniform all year round regardless of the weather.

The CTPS is also useful for: (1) the production of insect- and pesticide-free transplants, (2) shortening the transplant production period by 30%–40% compared with that using a greenhouse by optimally controlling the environment including CO₂ enrichment, (3) increasing the annual transplant productivity per unit land area, and (4) improving the traceability of the transplant production process (Kozai, 2006).

In this chapter, first, the main components and functions of the CTPS are described, as well as the annual productivity and electricity cost per transplant. Second, the ecophysiology of transplant production is discussed. Third, production schemes for several medicinal and horticultural transplants are described. Finally, the propagation and production of blueberry and strawberry transplants are introduced.

22.2 Main components and their functions

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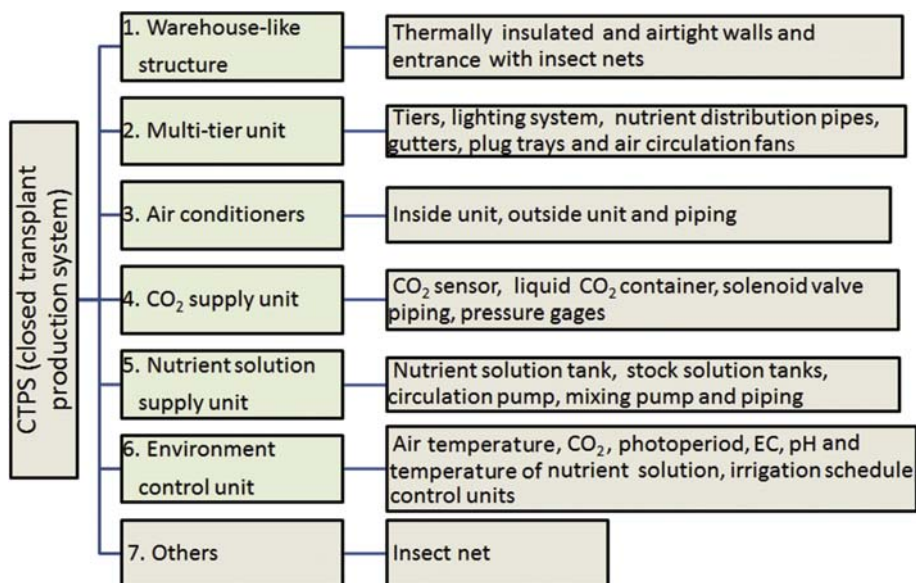


FIGURE 22.1

Main components of CTPS.

22.2.1 Main components

The CTPS has been commercially used since 2004 and is now used at more than 300 locations in Japan as of 2014. The main components of the CTPS are the same as those of the PFAL, as shown in Fig. 22.1. However, there are some unique characteristics of the CTPS which are somewhat different from those of the PFAL in order to produce the high-quality transplants mentioned in the introduction to this chapter.

The standard size of the basic CTPS unit being used in Japan is 4.5 m wide, 3.6 m long, and 2.4 m high (floor area: 16.2 m²) (see Fig. 22.2A) with two rows each having four tiers. This CTPS can hold 96 plug trays (each 30 cm wide × 60 cm long). By using plug trays each having 100 or 200 cells, 9600 or 19,200 transplants can be produced at one time. In the case of tomato seedling production, for example, it takes about 20 days after seeding or 17 days after germination to get the seedlings ready for transplanting. Therefore, the annual production capacity of one basic unit of CTPS is about 200,000 seedlings (= 9600 × 365/17) for 100-cell plug trays and 400,000 seedlings for 200-cell plug trays. The CO₂ concentration during the photoperiod is usually kept at around 1200 ppm to enhance the photosynthesis and thus growth. Liquid CO₂ in a pressurized container is used as the CO₂ source.

The basic units can be connected with each other as shown in Fig. 22.2B. In this case, extra facilities such as seeding machines, germination boxes, germination rooms, and insect net rooms are often installed next to the CTPS (Fig. 22.3).

22.2.2 Light source, air conditioners, and small fans

Fluorescent lamps (FLs) had been used as light sources since 2014 but they have been replaced by LED lamps since 2018. Five or six FLs (1.2 m long, 32 W) on each shelf provide a photosynthetic

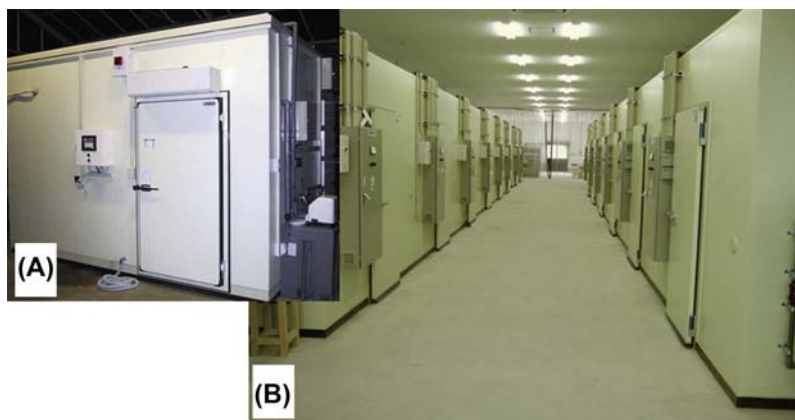


FIGURE 22.2

Exterior of CTPS. (A) Basic unit of CTPS (floor area: 16 m²) for a small-scale grower. (B) CTPS consisting of 21 basic units.

Photo courtesy of Mitsubishi Chemicals Inc.

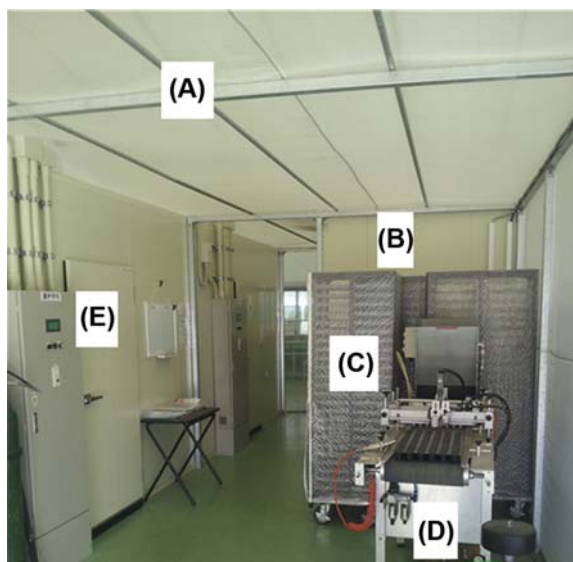


FIGURE 22.3

Extra facilities often used together with multiple CTPSs. (A) Insect net room to prevent insects from entering the CTPS; (B) germination room; (C) germination box to be placed in the germination room after seeding; (D) seeding machine, (E) CTPS.

FIGURE 22.4

Inside view of the plug tray shelf. Five to six FL (fluorescent) tubes (32 W each, $300\text{--}350\ \mu\text{mol m}^{-2}\ \text{s}^{-1}$) and four small sucking fans (2–3 W each) are installed for one shelf unit holding four plug trays.

Photo courtesy of Mitsubishi Chemicals Inc.



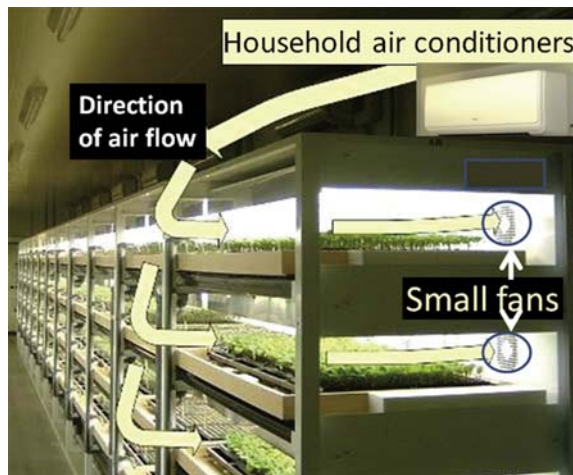
photon flux density (PPFD) of around 300 or $350\ \mu\text{mol m}^{-2}\ \text{s}^{-1}$ at the plug tray surface (Fig. 22.4). However, it should be noted that the PPFD decreases with time by about 30% after being used for 10,000 h in case of FLs.

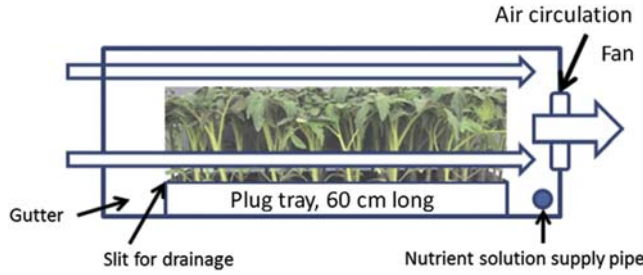
Four household air conditioners are installed above the tiers in the basic unit of CTPS. One small air circulation fan (electricity consumption: 6 W, air flow rate: $2.9\ \text{m}^3\ \text{min}^{-1}$) is installed for each plug tray, or four fans for four plug trays (Fig. 22.4). This arrangement of air conditioners and fans generates the air flow pattern shown in Fig. 22.5. With this arrangement, a relatively laminar horizontal air current is generated over the plug trays and through the transplant canopy in each shelf (Fig. 22.6). By using fans with an inverter for controlling the fan rotation speed, the air current speed over the transplant canopy is continuously controlled in a range between $20\ \text{cm s}^{-1}$ and $100\ \text{cm s}^{-1}$, depending on the transplant growth stage, planting density, transplant morphology, etc. The horizontal air current within the transplant canopy with a height of about 10–15 cm keeps the relative humidity in the transplant canopy lower than 85%, and hence elongation of hypocotyl (stem) can be avoided even at a planting density of 1.5–2.0 times that in a greenhouse (Fig. 22.7).

In most CTPS, no humidification unit is installed because the transpiration by plants and evaporation from the substrate humidify the room air. For a CTPS full of plug trays and with an air temperature of around 25°C , the relative humidity over the plug trays is kept at around 75%–80% by the balance between the evapotranspiration of liquid water and the condensation of water vapor by air conditioners. In contrast, the relative humidity tends to be as low as 50% when the CTPS is almost empty.

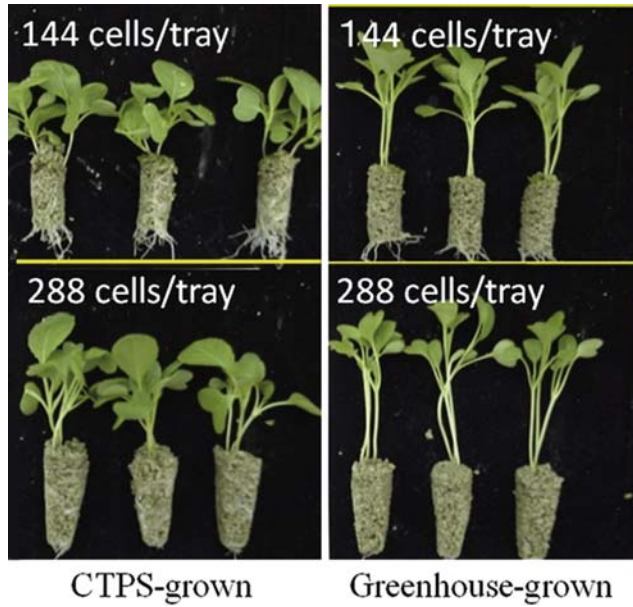
FIGURE 22.5

Air flow pattern in the CTPS. Uniform air currents over the plug trays are generated by using small suction fans inside the shelves and household air conditioners.



**FIGURE 22.6**

Schematic diagram of longitudinal section of the culture shelf. Arrows indicate the direction of air flow. Air current speed is uniform over the trays and within the transplant canopy, and can be controlled by a fan with inverter (see also Fig. 22.8).

**FIGURE 22.7**

A horizontal air flow of constant speed is generated inside the plant canopy, so the relative humidity inside the canopy is kept at about 85% or less, enabling high-density transplanting without elongation of hypocotyl of transplants.

22.2.3 Electricity costs

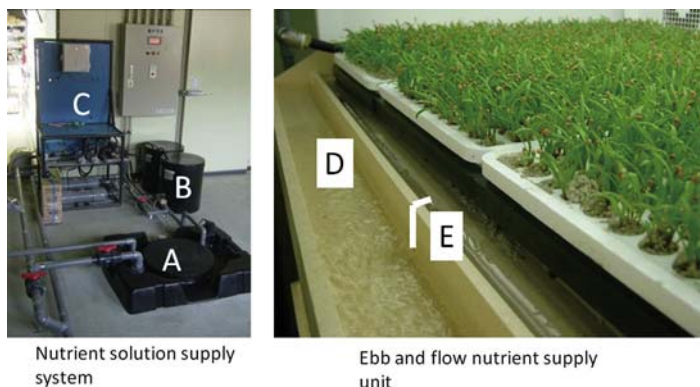
The electricity cost for lighting per transplant can be estimated easily as a function of electricity consumption per lamp (W), number of lamps per shelf (N_L), photoperiod hours per day (P), days required to produce the transplants after germination (D), and the number of cells per plug tray (N_P). Assuming that five fluorescent tubes ($N = 5$) are used for four plug trays ($30 \text{ cm} \times 4 = 120 \text{ cm}$) and that $W = 0.035 \text{ kW}$, $P = 16$, $D = 17$, and $N_P = 1280$ (these assumptions correspond to tomato seedling production), then the electricity consumption for lighting per transplant (E) is expressed by:

$$E = \frac{W \times N_L \times P \times D}{4 \times N_P} = \frac{0.035 \times 5 \times 16 \times 17}{4 \times 128} = 0.094 \text{ kWh} \quad (22.1)$$

If the price of electricity per kWh is US\$0.10 and 0.20, the electricity cost per transplant is US\$0.0094 ($= 0.12 \times 0.10$) and 0.019, respectively.

FIGURE 22.8

Left: Buried nutrient solution tank (A), two stock solution tanks (B), and the control unit (C). Right: Gutter for nutrient solution return (D), and the slit for adjusting the outflow rate and the level of nutrient solution in the culture bed (E). Nutrient solution which is not absorbed by the substrate is returned to the nutrient solution tank to be recycled.



The electricity cost for air conditioning, air circulation, and nutrient solution circulation is roughly one quarter of the cost for lighting (Kozai, 2007), so the total electricity cost per transplant is around $\text{US\$}0.012 = 0.094 \times ((80 + 20)/(80))$ or 0.026. Although electricity costs are incurred, (1) no labor or labor cost is required for pesticide application, (2) the land area used for transplant production is reduced by 90% compared with transplant production using a greenhouse, which greatly reduces the labor cost for handling the plug trays (Kozai, 2006, 2007), and (3) no heating cost is required during the photoperiod, and the heating cost is minimized even during the dark period because the CTPS is thermally well insulated and almost airtight.

22.2.4 Nutrient solution supply

Nutrient solution is typically supplied only once or twice using the ebb and flow system (Fig. 22.8) to restrict the water uptake by transplants and thus to produce transplants with thick and short stems. Drained nutrient solution is returned to the nutrient solution tank after filtering to be recycled. EC (electrical conductivity), pH, and temperature of nutrient solution can be controlled by installing controllers.

The CTPS is always cooled by air conditioners during the photoperiod to remove the heat energy generated by lamps. The water condensed at the cooling panel of air conditioners is also returned after filtering to the nutrient solution tank. Therefore, no drainage pipes are required in the CTPS. By recycling the nutrient solution and condensed water, the water consumption of the CTPS is about 90% less than that of a greenhouse (Kozai, 2007).

22.3 Ecophysiology of transplant production

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22.3.1 Introduction

The optimization of plant growth is one of the most important objectives of plant production in controlled environments. Most studies have focused on quantitative growth. Recent studies have also

focused on the improvement of qualitative growth through specific nutrient components by controlling physical environmental factors. In transplant production, plant quality should be evaluated from different aspects than for fruit and vegetable production: as greenhouse growers demand transplants which have high productivity after transplantation, the quality of transplants should be evaluated in terms of their growth potential (measured as photosynthetic performance and biotic and abiotic stress resistance) after transplantation. Growth potential is strongly affected by ecophysiological responses to physical environmental factors; plants sense factors such as temperature, humidity, and light, and acclimatize accordingly. In CTPS in which these factors can be controlled (Kozai et al., 2006; Kozai, 2007), controlling the factors might therefore improve the growth potential of transplants.

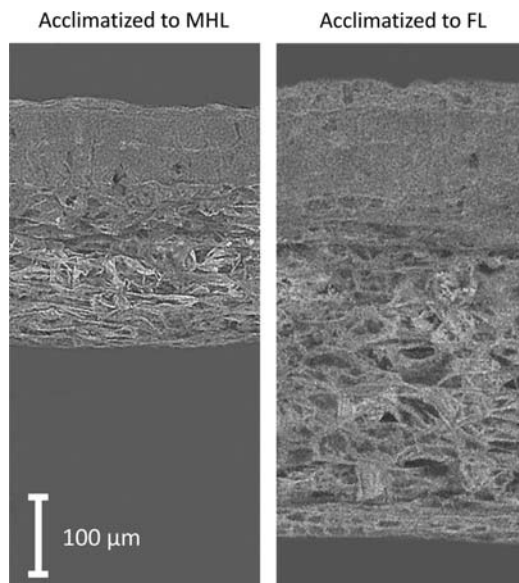
In addition to plant–environment interactions, plant–plant interactions are important for improving the quality of densely grown transplants, because the micrometeorology within the plant canopy depends on the structure of and gas exchange within the plant canopy, which depend on interactions between neighboring plants. Thus, it is important to understand these interactions in order to optimally control the environmental factors.

This section describes the plant–environment interactions and plant–plant interactions in transplant production from an ecophysiological viewpoint.

22.3.2 Effects of light quality on photosynthetic performance in transplants

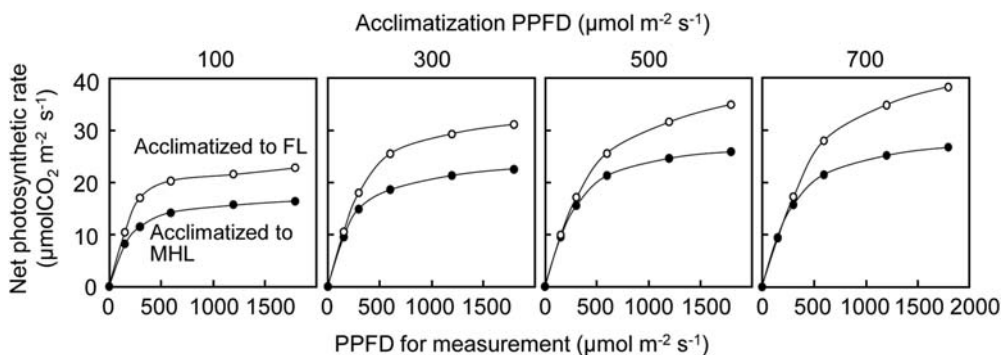
Light is one of the most important factors for the ecophysiological acclimatization of plants to their environment. The light environment determines photosynthetic performance (Lichtenthaler et al., 1981). Leaves acclimatized to bright light (sun leaves) have a greater maximum photosynthetic rate, whereas those acclimatized to dim light (shade leaves) have a lower light compensation point (LCP). In addition to light quantity, light quality, which is indicated by the ratio of red to far-red light (R:FR), determines photosynthetic acclimatization. In natural ecosystems, the absorption of red light by neighboring vegetation reduces the R:FR, which increases shoot elongation and leaf expansion and decreases leaf thickness (Smith and Whitelam, 1997). This “shade avoidance” response allows plants to tolerate or avoid shading (Franklin, 2008).

The R:FR ratio also affects physiological and morphological properties when it is greater than that of natural light. The typical commercial FLs used in CTPS emit little FR light, making their R:FR generally much greater than that of natural sunlight. Leaves acclimatized to a higher R:FR are thicker (Fig. 22.9) and have more chlorophyll, thereby improving their photosynthetic performance. Shibuya et al. (2010a) compared photosynthetic performance between leaves acclimatized to illumination from metal halide lamps (MHLs) with spectra similar to that of natural light (R:FR = 1.2) and that from FLs with a high R:FR (= 11). The maximum photosynthetic rate of FL-acclimatized leaves was 1.4 times that of MHL-acclimatized leaves at a range of light intensities (Fig. 22.10). The photosynthetic and morphological characteristics of high-R:FR-acclimatized leaves were similar to those of sun leaves (Lichtenthaler et al., 1981). The response curve of FL-acclimatized leaves at the acclimatization photosynthetic photon flux (PPF) of $100 \mu\text{mol m}^{-2} \text{s}^{-1}$ was almost the same as that of MHL-acclimatized leaves at $300 \mu\text{mol m}^{-2} \text{s}^{-1}$. This indicates that a photosynthetic performance equivalent to that of plants acclimatized to natural light can be obtained by FL acclimatization with one third the quantity of light. This greater photosynthetic performance results from a greater biomass for photosynthesis per unit leaf area and from a higher stomatal density and greater stomatal size (Shibuya et al., 2015). These results mostly agree with the report that an increased proportion of active phytochrome, which is correlated

**FIGURE 22.9**

Cross-sections of cucumber cotyledons acclimatized to illumination from metal halide lamps (MHL) with spectra similar to that of natural light (R:FR = 1.2) or fluorescent lamps (FL) with high R:FR (= 11).

Modified from Shibuya, T., Itagaki, K., Tojo, M., Endo, R., Kitaya, Y., 2011. Fluorescent illumination with high red-to-far-red ratio improves resistance of cucumber seedlings to powdery mildew. HortScience 46, 429–431.

**FIGURE 22.10**

Light response curves of cucumber seedlings acclimatized to different light qualities and quantities. MHL: metal halide lamps with spectra similar to those of natural light (R:FR = 1.2); FL: fluorescent lamps with high R:FR (= 11).

Modified from Shibuya, T., Endo, R., Hayashi, N., Kitaya, Y., 2012. High-light-like photosynthetic responses of Cucumis sativus leaves acclimated to fluorescent illumination with a high red:far-red ratio: interaction between light quality and quantity. Photosynthetica 50, 623–629.

with R:FR, enhances stomatal development (Boccalandro et al., 2009). However, the resultant increased stomatal conductance of high-R:FR-acclimatized leaves reduces the water-use efficiency (= net photosynthetic rate/transpiration rate) below that of normal-R:FR-acclimatized leaves. This lower water-use efficiency may be disadvantageous when plants must be moved to water-deficit conditions, such as during transplantation for horticultural production. Thus, it may be necessary to monitor and prevent water stress when transplanting high-R:FR-acclimatized plants.

The heightened photosynthetic performance of high-R:FR-acclimatized leaves reflects the opposite physiological and morphological responses typical of shade avoidance. This acclimatization is probably advantageous when plants are to be transplanted to high-PPF conditions. On the other hand, high-R:FR illumination inhibits leaf expansion and consequent plant growth during the acclimatization period. This is probably due to greater allocation of biomass to leaf thickening. Trade-offs between quantitative growth and plant defense against environmental stress cause changes in the distribution of biomass (Bazzaz et al., 1987). The acclimatization to higher light intensity that results from a high R:FR may be a defense against environmental stress. In this case, there may be a trade-off between faster growth and improved photosynthetic performance, which is beneficial under higher light intensity. When selecting artificial light for transplant production, we may need to consider which of the two advantages is more important.

22.3.3 Effects of the physical environment on biotic stress resistance in transplants

Plants acclimatized under shade have less resistance to herbivores and pathogens (McGuire and Agrawal, 2005; Ballaré, 2009; Moreno et al., 2009; Cerrudo et al., 2012). Conversely, plants acclimatized under high-R:FR light have improved resistance to biotic stress. High-R:FR light improved powdery mildew resistance in cucumber seedlings (Shibuya et al., 2011). High-R:FR-acclimatized leaves had thicker epidermis, palisade, and spongy mesophyll (Fig. 22.9). As the morphological properties of host plants affect the severity of pathogenic fungal infection (Szwacka et al., 2009), the improved powdery mildew resistance in high-R:FR-acclimatized leaves might be due in part to morphological changes induced by the improved acclimatization to light described above. There are many reports that plant resistance to diseases can be improved by illumination at particular wavelengths (e.g., Wang et al., 2010). Acclimatization to light quality also affects plant–herbivore interactions. Shibuya et al. (2010b) evaluated the preference of adult sweet potato whitefly for cucumber seedlings that had been acclimatized to FL or MHL; there were significantly fewer whitefly adults on FL-acclimatized seedlings, which had a deeper color and thicker leaves, 24 h after release. Environmental factors often have indirect effects on herbivore behavior through their effects on the morphological and physiological characteristics of plants (Berlinger, 1986; Waring and Cobb, 1992; McAuslane, 1996; Chu et al., 1999). The difference in preference of whitefly adults between FL- and MHL-acclimatized leaves may be explained by the morphological characteristics which were induced by light quality. Low-R:FR light strongly reduced plant sensitivity to jasmonates, which are key regulators of plant immunity (Moreno et al., 2009). Therefore, it is likely that the powdery mildew resistance of high-R:FR leaves was improved not only through morphological changes, but also through systemic defense mechanisms.

A similar phenomenon can be observed when humidity is changed. Humidity influences the properties of the leaf surface, and consequently its resistance to water loss (Koch et al., 2006). The

structural properties that protect against water loss through the epidermis also have an important function in a plant's interaction with fungal pathogens. In inoculation tests, infection by powdery mildew fungus was inhibited on leaves that had been acclimatized to a high vapor-pressure deficit (VPD) compared with leaves that had been acclimatized to low VPD (Itagaki et al., 2014). The high-VPD-acclimatized leaves were thicker and had greater dry mass per area. The inhibition was caused mainly by changes in leaf morphological properties for protecting against water loss. Humidity also affects plant–herbivore interactions through host-plant responses. Adult sweet potato whitefly preferred low-VPD-acclimatized leaves to high-VPD-acclimatized leaves, which are thicker and darker and have more trichomes (Shibuya et al., 2009a).

Protection from environmental stresses is essential for plant survival. Typical defense responses include improvement of systemic resistance through antioxidant systems and hardening of epidermal ultrastructure. The improved biotic resistance described in the preceding paragraphs probably results from defense against higher light intensity in high-R:FR-acclimatized plants and against excess water loss in high-VPD-acclimatized plants. But the biomass allocation required for improvement of defense can affect other plant properties. For example, leaf structure is hardened at the expense of a lower leaf expansion rate. This suggests that plant defense takes priority over leaf expansion in the allocation of biomass. Therefore, there would be trade-offs between the growth rate during transplant production and the potential growth ability after transplantation. Transplant growers may have to optimize the environmental conditions to balance these two conflicting benefits.

22.3.4 Effects of plant–plant interactions on gas exchange within transplant canopy

In transplant production, seedlings are often grown densely. Gas exchange between plants and the atmosphere occurs through the boundary layer above the plant canopy. The thickness of the boundary layer depends on factors such as air currents and the structure of the plant canopy, and affects micrometeorological factors such as air temperature, vapor pressure, CO₂ concentration, and air currents within the canopy (Kitaya et al., 1998). In the small volume of the seedling canopy, these factors and the structure of the plant canopy interdependently determine gas exchange, which reciprocally affects the micrometeorology. It is important to clarify this relationship for controlling gas exchange and consequent plant growth.

As the leaf area index (LAI, total leaf area per unit ground area) of the plant canopy increases, the resultant mutual shading reduces the photosynthetic rate per unit leaf area. Reduced gas exchange between leaves and the atmosphere due to the decrease in CO₂ concentration and air currents around the leaves also limits photosynthesis (Kitaya et al., 2003). Thus, controlling air currents is essential to improve gas exchange. Along with the air current speed, the direction of air flow is equally important for the control of gas exchange. Shibuya et al. (2006) investigated the effects of air current direction on photosynthesis of tomato transplant canopy in a forced-ventilation system (Fig. 22.11). When the LAI increased from 1.2 to 2.4, conventional horizontal airflow above the canopy reduced the net photosynthetic rate per unit leaf area by 20%, whereas downward airflow reduced it by only 5% (Fig. 22.12). The greater reduction in the horizontal system was probably due to limited CO₂ supply into the canopy through the boundary layer.

Photosynthesis can conversely increase with increasing LAI when photosynthesis is mainly limited by a decrease in the stomatal aperture resulting from water stress. For example, Shibuya et al. (2009b) showed that photosynthesis increased with increasing LAI under high VPD (low humidity) conditions. This phenomenon can be explained by changes in transpiration rate and stomatal conductance

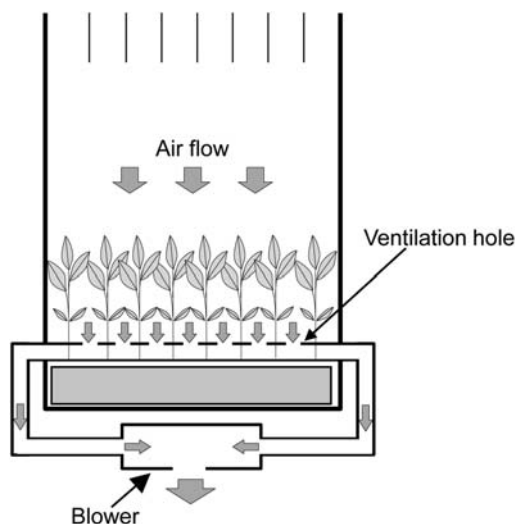


FIGURE 22.11

Plant culture system with forced ventilation within the canopy.

Modified from Shibuya, T., Tsuruyama, J., Kitaya, Y., Kiyota, M., 2006. Enhancement of photosynthesis and growth of tomato seedlings by forced ventilation within the canopy. *Sci. Hortic.* 109, 218–222.

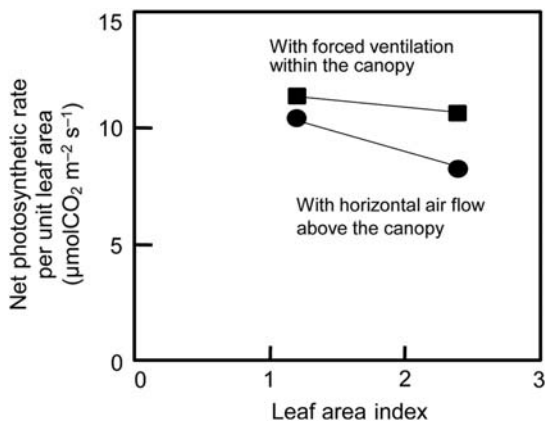


FIGURE 22.12

Effect of forced ventilation on photosynthesis of tomato transplant canopy at different leaf area indexes.

Modified from Shibuya, T., Tsuruyama, J., Kitaya, Y., Kiyota, M., 2006. Enhancement of photosynthesis and growth of tomato seedlings by forced ventilation within the canopy. *Sci. Hortic.* 109, 218–222.

(Fig. 22.13). As plant density increases, the VPD within the canopy tends to decrease, probably owing to a thickening boundary layer above the canopy, decreasing the transpiration rate per unit leaf area, which mitigates water stress. In summary, as LAI increases, the thickening boundary layer decreases the VPD within the canopy, mitigating the stomatal closure that occurs due to excessive transpiration,

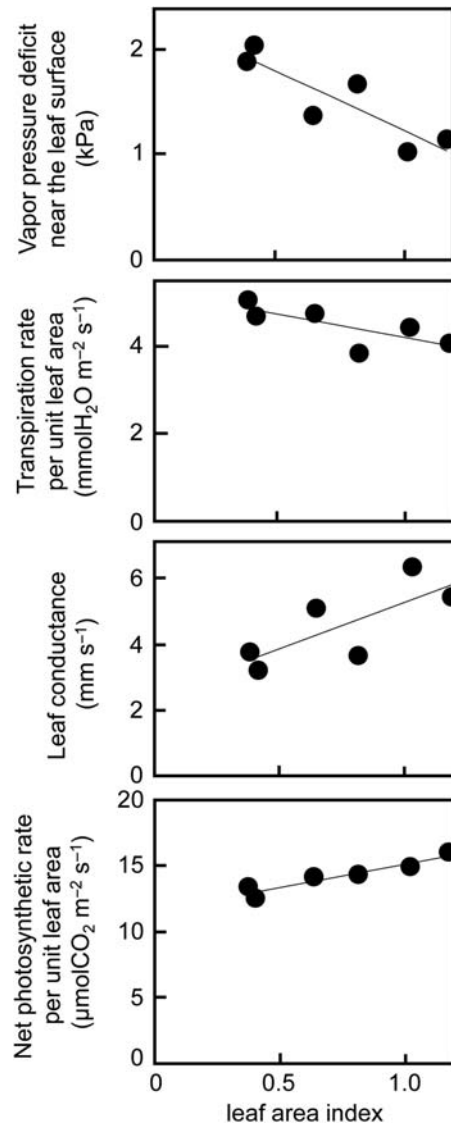


FIGURE 22.13

Relationships between leaf area index and vapor-pressure deficit, transpiration, leaf conductance, and photosynthesis under low humidity (the vapor-pressure deficit above the canopy was 3.7 kPa).

Modified from Shibuya, T., Sugimoto, A., Kitaya, Y., Kiyota, M., 2009b. High plant density of cucumber (*Cucumis sativus* L.) seedlings mitigates inhibition of photosynthesis resulting from high vapor-pressure-deficit. *Hortscience* 44, 1796–1799.

thus increasing photosynthesis. This is a good example of the complex interdependence among gas exchange by plants, micrometeorological factors, and the structure of the plant canopy.

22.3.5 Effects of light quality on light competition between neighboring plants and consequent equality of plant growth

The effects of light quality on plant growth have been thoroughly investigated, but those on the structure of plant canopy less so. Changes in light quality due to competition between neighboring plants strongly affect plant growth and morphology; for example, a reduction in the R:FR increases shoot elongation. Competition also affects the structure of a plant community: plants regulate their growth to achieve a height similar to that of their neighbors (Ballaré et al., 1994; Nagashima and Hikosaka, 2011, 2012). This process is called “height convergence” (Nagashima and Terashima, 1995). The pattern of height convergence is affected by the R:FR of background illumination, because the effects of reduced R:FR by neighboring vegetation on the shade avoidance response differ with the value of R:FR: Shibuya et al. (2013) investigated the effects of the R:FR of background illumination on the height convergence pattern in dense plant canopy by growing cucumber seedlings of the same age but with different initial heights under MHL or FL (Fig. 22.14). The shoot heights of the initially taller and shorter seedlings under MHL converged within 4 days, whereas those under FL did not reach convergence within 8 days (Fig. 22.15). The rapid height convergence under MHL occurred as a result of the shade avoidance response of the initially shorter seedlings stimulated by the decreased R:FR. The slower height convergence under FL is due to an insufficient R:FR level to stimulate the shade avoidance response of the shorter seedlings because of the much higher R:FR of the background illumination. These results suggest that unequal growth of plants is likely to occur under illumination with a high R:FR, because height convergence is hindered. The even plant growth needed for commercial transplant production results from light competition between neighboring plants, which simultaneously causes shoot elongation. However, excess shoot elongation can decrease the commercial value of transplants, because plants with long and narrow stems are easily damaged by environmental stresses and by the handling that occurs during transportation and transplantation of the transplants. So there may be a trade-off between even plant growth and shorter stems, both of which are valuable for transplant growers, but which are both inversely controlled by the same ecophysiological mechanism.

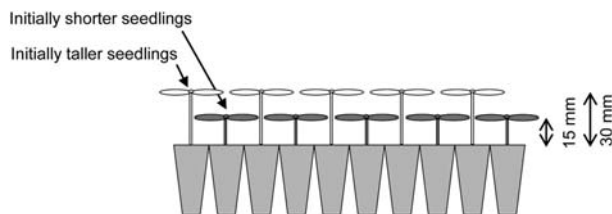


FIGURE 22.14

Cucumber seedlings of the same age but with different initial heights (30 and 15 mm) used to evaluate height convergence.

Modified from Shibuya, T., Takahashi, S., Endo, R., Kitaya, Y., 2013. Height-convergence pattern in dense plant stands is affected by red-to-far-red ratio of background illumination. Sci. Hortic. 160, 65–69.

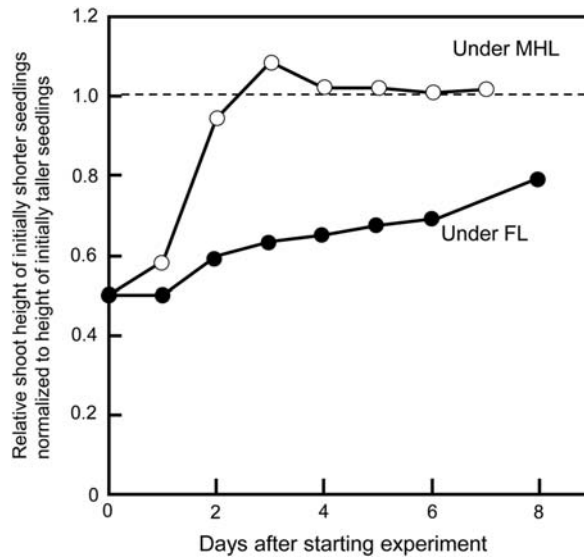


FIGURE 22.15

Time courses of shoot height of the initially shorter seedlings of cucumber in the plant canopy, normalized to the value of the initially taller seedlings, under illumination from metal halide lamps (MHL) with spectra similar to that of natural light (R:FR = 1.2) or fluorescent lamps (FL) with high R:FR (= 11).

Modified from Shibuya, T., Takahashi, S., Endo, R., Kitaya, Y., 2013. Height-convergence pattern in dense plant stands is affected by red-to-far-red ratio of background illumination. Sci. Hortic. 160, 65–69.

22.3.6 Conclusions

In natural ecosystems, plants grow by optimizing the allocation of their limited biomass for acclimatization to environmental conditions. In plant production, however, this allocation does not always give optimal results. In addition, there is a trade-off between plant growth and plant quality. Thus, growers may have to balance conflicting benefits through environmental control in order to optimize plant growth and quality. Ecophysiological responses to plant–environment and plant–plant interactions must be considered in improving plant production systems, particularly now that many environmental control devices and plant control methods have been developed.

22.4 Photosynthetic characteristics of vegetable and medicinal transplants as affected by the light environment

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22.4.1 Introduction

Light is one of the most important environmental factors in a PFAL, influencing the growth, morphogenesis, and other physiological processes of plants. The three most important elements in the light environment for plant growth are light intensity or PPFD, photoperiod, and light quality. High-quality transplants can be produced by appropriately controlling the light environment. This section describes the photosynthetic characteristics of cucumber and tomato transplants and a medicinal plant, *Dendrobium officinale*, as affected by the light environment.

22.4.2 Influence of the light environment on vegetable transplant production

The lighting cost in a PFAL accounts for a significant percentage of the total production cost (Kozai, 2007, 2013a). Characterizing the photosynthetic response of transplants to different PPFDs will help determine the most cost-effective PPFD for vegetable transplant production. Typically, net photosynthetic rate (P_n) increases with increasing PPFD within the range between the LCP and the light saturation point (LSP). The LCP is the PPFD at which P_n is equal to the respiration rate, and the LSP is the PPFD at which P_n no longer increases with increases in PPFD.

In Fig. 22.16, P_n of tomato (*Lycopersicon esculentum* Mill., cv. Zhongza No. 9) and pepper (*Capsicum annuum* L., cv. CAU No. 24) transplants increases linearly as PPFD increases at PPFD below $300 \mu\text{mol m}^{-2} \text{s}^{-1}$. The slope of the increase of P_n becomes smaller when PPFD is higher than $300 \mu\text{mol m}^{-2} \text{s}^{-1}$ and lower than $600 \mu\text{mol m}^{-2} \text{s}^{-1}$, then reaches a plateau phase. Therefore, from an economic point of view and light use efficiency (for more information, refer to Chapter 5), increasing PPFD to higher than $300 \mu\text{mol m}^{-2} \text{s}^{-1}$ would be less efficient for vegetable transplant production in a PFAL. Similar to PPFD, P_n of the above tomato and pepper transplants increases linearly with CO_2 concentration. However, for tomato transplants, when CO_2 concentration is higher

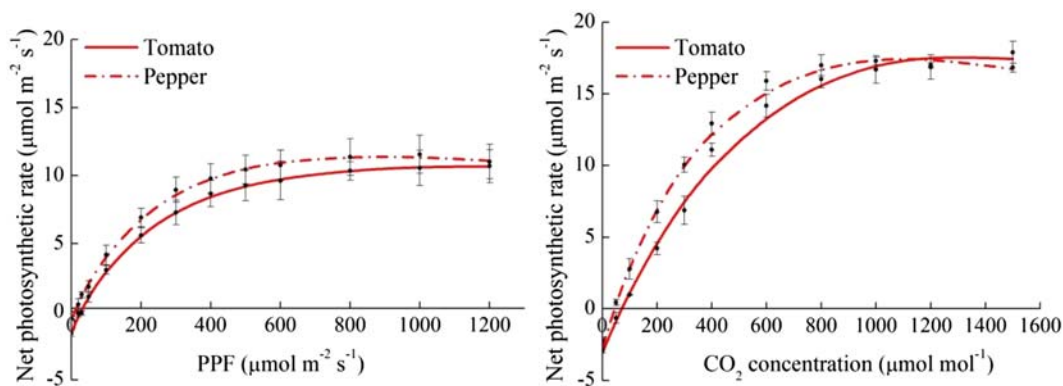


FIGURE 22.16

The response curve of net photosynthetic rates of tomato and pepper transplants to photosynthetic photon flux density (PPFD) and CO_2 concentration. Environmental conditions of air temperature, relative humidity, PPFD, and photoperiod were maintained at $24.0 \pm 1.5^\circ\text{C}$, $60 \pm 5\%$, $250 \mu\text{mol m}^{-2} \text{s}^{-1}$, and 12 h day^{-1} , respectively.

than $1000 \mu\text{mol mol}^{-1}$, P_n does not increase significantly with a further increase in CO_2 concentration. For pepper transplants, the CO_2 saturation concentration is about $800 \mu\text{mol mol}^{-1}$. Therefore, the PPFD and CO_2 concentration in a PFAL should be controlled according to their photosynthetic characteristics and resource use efficiency (Fig. 22.16).

22.4.3 Effects of PPFD and photoperiod on the growth of vegetable transplants

In order to identify the most cost-effective light environment for vegetable transplant production in a PFAL, cucumber (*Cucumis sativus* L., cv. CAU No. 26) transplants were grown under different combinations of PPFD and photoperiod: PPFD of 100, 200, 250, and $300 \mu\text{mol m}^{-2} \text{s}^{-1}$ and photoperiods of 12 and 16 h day^{-1} (Table 22.1). Air temperature in the photoperiod and dark period, relative humidity, and CO_2 concentration were maintained at $26.0 \pm 1.0^\circ\text{C}/22.0 \pm 1.0^\circ\text{C}$, $65 \pm 5\%$, and $800 \pm 100 \mu\text{mol mol}^{-1}$, respectively. Biomass at the PPFD of $100 \mu\text{mol m}^{-2} \text{s}^{-1}$ and photoperiod of 12 h day^{-1} was less than those under all the other conditions. Shoot mass was the greatest at the PPFD of $200 \mu\text{mol m}^{-2} \text{s}^{-1}$ and photoperiod of 16 h day^{-1} , whereas root mass was the greatest under the PPFDs of 200 and $250 \mu\text{mol m}^{-2} \text{s}^{-1}$ and photoperiod of 16 h day^{-1} . In conclusion, the PPFD of 200–250 $\mu\text{mol m}^{-2} \text{s}^{-1}$ is effective for transplant production, and extending the photoperiod from 12 to 16 h day^{-1} can increase the biomass and growth of cucumber transplants in a PFAL. For commercial transplant production in a PFAL, the PPFD could be designed and controlled up to $250 \mu\text{mol m}^{-2} \text{s}^{-1}$.

Table 22.1 Influence of photosynthetic photon flux density (PPFD) and photoperiod on fresh mass and dry mass of cucumber transplants.

Treatments		Fresh mass (g plant^{-1})		Dry mass (mg plant^{-1})	
Photoperiod (h day^{-1})	PPFD ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	Shoot	Root	Shoot	Root
12	100	$2.60 \pm 0.22\text{d}^{\text{a}}$	$0.60 \pm 0.15\text{d}$	$190.0 \pm 30.3\text{e}$	$21.7 \pm 4.1\text{d}$
	200	$3.77 \pm 0.27 \text{cd}$	$1.18 \pm 0.44\text{c}$	$318.3 \pm 23.2\text{d}$	$40.0 \pm 16.7\text{c}$
	250	$3.47 \pm 0.46 \text{cd}$	$1.75 \pm 0.29\text{b}$	$311.7 \pm 63.1\text{d}$	$60.0 \pm 15.5\text{b}$
	300	$4.39 \pm 0.69\text{c}$	$1.55 \pm 0.43\text{bc}$	$441.7 \pm 104.8\text{c}$	$66.7 \pm 25.8\text{b}$
16	100	$4.59 \pm 0.80\text{c}$	$1.00 \pm 0.35\text{c}$	$341.7 \pm 78.9 \text{cd}$	$38.3 \pm 16.0\text{c}$
	200	$8.60 \pm 1.46\text{a}$	$2.42 \pm 0.70\text{a}$	$760.0 \pm 175.5\text{a}$	$88.3 \pm 21.4\text{ab}$
	250	$7.80 \pm 0.61\text{ab}$	$2.72 \pm 0.21\text{a}$	$635.0 \pm 86.7\text{b}$	$106.7 \pm 10.3\text{a}$
	300	$7.17 \pm 0.81\text{b}$	$2.46 \pm 0.63\text{a}$	$618.3 \pm 69.1\text{b}$	$100.0 \pm 30.1\text{a}$
ANOVA					
PPFD		*	*	*	*
Photoperiod		*	*	*	*
PPFD*Photoperiod		*	NS	*	NS

^aMeans with different letters in the same column are significantly different tested by SPSS multiple comparison at $P = .05$.

22.4.4 Effects of light quality on growth of vegetable transplants

The spectral characteristics of artificial lighting should meet the physiological requirements of plants for photosynthesis and morphological development (Fraszczak, 2014; Vu et al., 2014; Wesley and Lopez, 2014). The influence of different spectral distributions of light at the PPFD of $200 \mu\text{mol m}^{-2} \text{s}^{-1}$ at the canopy level on the growth of vegetable transplants were studied using: white LED lamps (WL), triphosphate fluorescent lamps (TR), high-frequency fluorescent lamps (HF), and red and blue LED lamps (RB) to determine the suitable spectral characteristics (Fig. 22.17). Air temperature, relative humidity, CO_2 concentration, PPFD, and photoperiod were maintained at $25.0 \pm 1.5^\circ\text{C}$, $60 \pm 5\%$, $600 \pm 30 \mu\text{mol mol}^{-1}$, $200 \mu\text{mol m}^{-2} \text{s}^{-1}$, and 12 h day^{-1} , respectively.

The net photosynthetic rate of tomato transplants (*L. esculentum* Mill., cv. Zhongza No. 9) under the RB LED lamps was 12.5%–21.2% higher than those under other broad-band white light sources (Table 22.2). However, the stomatal conductance, intercellular CO_2 concentration, and transpiration rate were higher under the WL (R:B of 1) and HF (R:B of 3) lamps than under the TR (R:B of 2) and RB (R:B of 4) lamps. Broad-band white light can increase plant height and promote stem elongation of tomato transplants more effectively than RB LED light. Different light quality had no influence on seedling index [height $\times$ (shoot dry mass + root dry mass)/stem diameter] of tomato transplants. The results revealed that RB LED can promote photosynthesis and increase instantaneous water use efficiency of tomato transplants, whereas broad-band white light can increase plant height and promote stem elongation. However, there are big differences in the growth response to light quality among horticultural crops (van Ieperen, 2012). Research is needed to investigate the appropriate light environment for the production of different vegetable transplants in PFALs.

22.4.5 Photosynthetic characteristics of medicinal *D. officinale*

D. officinale, a medicinal plant endemic to China, is a rare and endangered orchid called “Plant Gold.” Although the cultivated area of *D. officinale* is gradually expanding, its yield cannot meet the market demand because of the slow growth rate. Transplants of *D. officinale* are typically propagated through

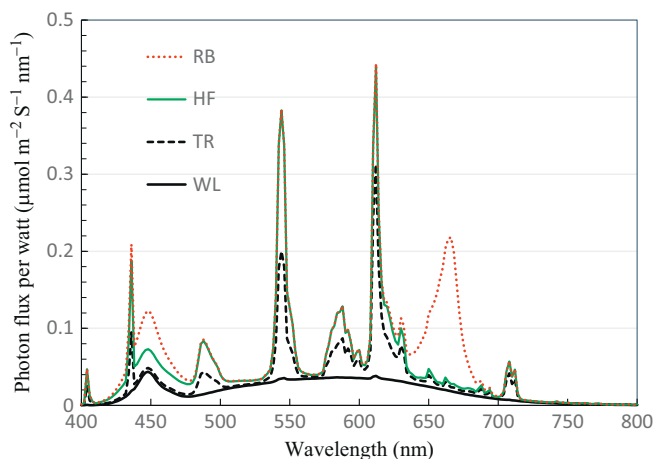


FIGURE 22.17

Spectral distributions of photon flux of different light sources, including white LED lamps (WL, R:B = 1), triphosphate fluorescent lamps (TR, R:B = 2), high-frequency fluorescent lamps (HF, R:B = 3), and red and blue LED lamps (RB, R:B = 4) at the photosynthetic photon flux of $200 \mu\text{mol m}^{-2} \text{s}^{-1}$ at the canopy surface in a PFAL. R:B is red to blue light ratio.

Table 22.2 Influence of different light sources (LS): white LED lamps (WL), triphosphate fluorescent lamps (TR), high-frequency fluorescent lamps (HF), and red and blue LED lamps (RB) on photosynthetic parameters of tomato transplants grown at air temperature of $25.0 \pm 1.5^\circ\text{C}$, relative humidity of $60 \pm 5\%$, CO_2 concentration of $600 \pm 30 \mu\text{mol mol}^{-1}$, photosynthetic photon flux density (PPFD) of $200 \mu\text{mol m}^{-2} \text{s}^{-1}$, and photoperiod of 12 h day^{-1} .

LS	R: B ^a	Net photosynthetic rate ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	Stomatal conductance ($\text{mol m}^{-2} \text{s}^{-1}$)	Intercellular CO_2 concentration ($\mu\text{mol mol}^{-1}$)	Transpiration rate ($\text{mmol m}^{-2} \text{s}^{-1}$)
WL	1	6.9 ± 0.7^b	$0.209 \pm 0.072a$	$329 \pm 20a$	$4.17 \pm 1.16a$
TR	2	$6.3 \pm 0.8b$	$0.121 \pm 0.052b$	$287 \pm 54b$	$2.58 \pm 0.93b$
HF	3	$7.0 \pm 0.9b$	$0.204 \pm 0.093a$	$327 \pm 30a$	$3.89 \pm 1.47a$
RB	4	$8.0 \pm 0.4a$	$0.117 \pm 0.051b$	$279 \pm 49b$	$2.13 \pm 1.08b$

^aR:B is red to blue ratio.

^bMeans with different letters in the same column are significantly different tested by SPSS multiple comparison at $P = 0.05$.

tissue culture, while mature plants are produced in protected structures such as high tunnels and greenhouses. It takes 4–5 years from tissue culture to mature plant. Due to its high economic value, slow growth, and diminishing wild population, cultivation in PFALs has great potential to promote the growth and development of *D. officinale* transplants. According to the literature (Ritchie and Buntawin, 2010) and our research results (Zhang et al., 2014), *D. officinale* is a facultative crassulacean acid metabolism (CAM) plant and its photosynthetic pathway shifts between C3 and CAM, depending on environmental conditions.

Using a continuous photosynthesis measurement system, CO_2 exchange rates of the whole shoots of *D. officinale* plants were measured for two consecutive days. In the PFAL with a relatively constant environment (PPFD of $164 \mu\text{mol m}^{-2} \text{s}^{-1}$ and daily average air temperature of $26.2 \pm 1.2^\circ\text{C}$), the maximum net CO_2 exchange rate of *D. officinale* reached $3.5 \mu\text{mol m}^{-2} \text{s}^{-1}$, then decreased slightly and maintained a positive net CO_2 exchange rate throughout the photoperiod (Fig. 22.13). Positive, low net CO_2 exchange rates were detected during the dark period. Net CO_2 exchange rates of *D. officinale* plants grown in a commercial greenhouse in Zhejiang province were measured on a sunny day (the first day, 23 April 2012, maximum PPFD inside the leaf chamber reached $168 \mu\text{mol m}^{-2} \text{s}^{-1}$) and a rainy day (the second day, 24 April 2012, maximum PPFD inside the leaf chamber reached $85 \mu\text{mol m}^{-2} \text{s}^{-1}$). The net CO_2 exchange rate reached a maximum of 4.0 and $1.6 \mu\text{mol m}^{-2} \text{s}^{-1}$ at 2 h after sunrise on both days and the percentages from the dark period were 31% and 29%, respectively (Fig. 22.18). *D. officinale* showed a typical CAM photosynthetic pattern on the sunny day, whereas the duration of positive CO_2 exchange rates during the daytime was longer on the rainy day.

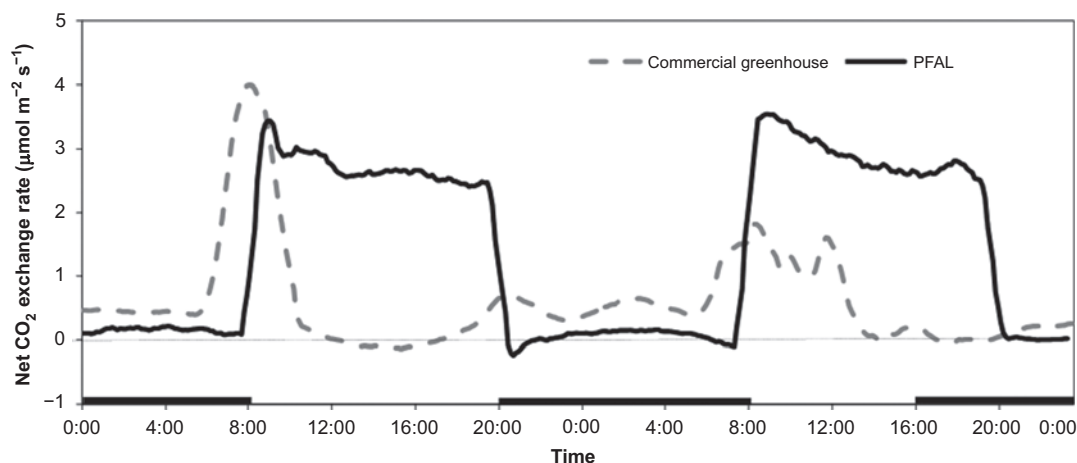


FIGURE 22.18

Time course of net CO₂ exchange rates of *D. officinale* in a PFAL and a commercial greenhouse. Dark bars on the x-axis indicate the dark periods in the PFAL.

Water deficit is one of the main factors inducing photosynthetic pathway switching, especially for facultative CAM plants. Fig. 22.19 shows the time course of net CO₂ exchange rates and the percentage of net CO₂ exchange during the dark period to the daily amount of *D. officinale* in a PFAL for 18 days. Irrigation was withheld for the first 12 days. At the end of the photoperiod on day 12, plants were rewatered. With decreasing substrate water content, the net CO₂ exchange rate of *D. officinale* decreased, and it increased again instantly after rewatering. The percentage of net CO₂ exchange rate during the dark period to the daily amount on day 12 was 51%, 189% higher than on day 1. By day 18, this percentage decreased by 76% compared to that on day 12. Under drought stress, a dominating CO₂ exchange pattern for *D. officinale* was CAM, and concomitance of C3 and CAM patterns were found again when the plants were rewatered.

The net CO₂ exchange rate of *D. officinale* increased rapidly after the onset of the photoperiod and decreased again in 4–6 h in the PFAL (Fig. 22.20). Therefore, shortening the light–dark cycles from 24 to 8 h or 12 h (8 and 12 h cycles with equal length of photoperiod and dark period, that is, 4 h light and 4 h dark and 6 h light and 6 h dark, respectively) may increase the daily net CO₂ exchange rate and promote biomass accumulation. When photoperiod and dark periods were shortened, net CO₂ exchange rates in the dark period changed significantly. At the 8 h cycle, a typical C3 photosynthetic pattern was observed and there was little positive net CO₂ exchange rate in the dark period. The positive net CO₂ exchange rate in the dark period indicated a higher degree of CAM photosynthetic pattern under the 24 h cycle compared to the 12 h cycle. In conclusion, adjusting light–dark cycles can induce CO₂ assimilation pattern switching between C3 and CAM in *D. officinale*.

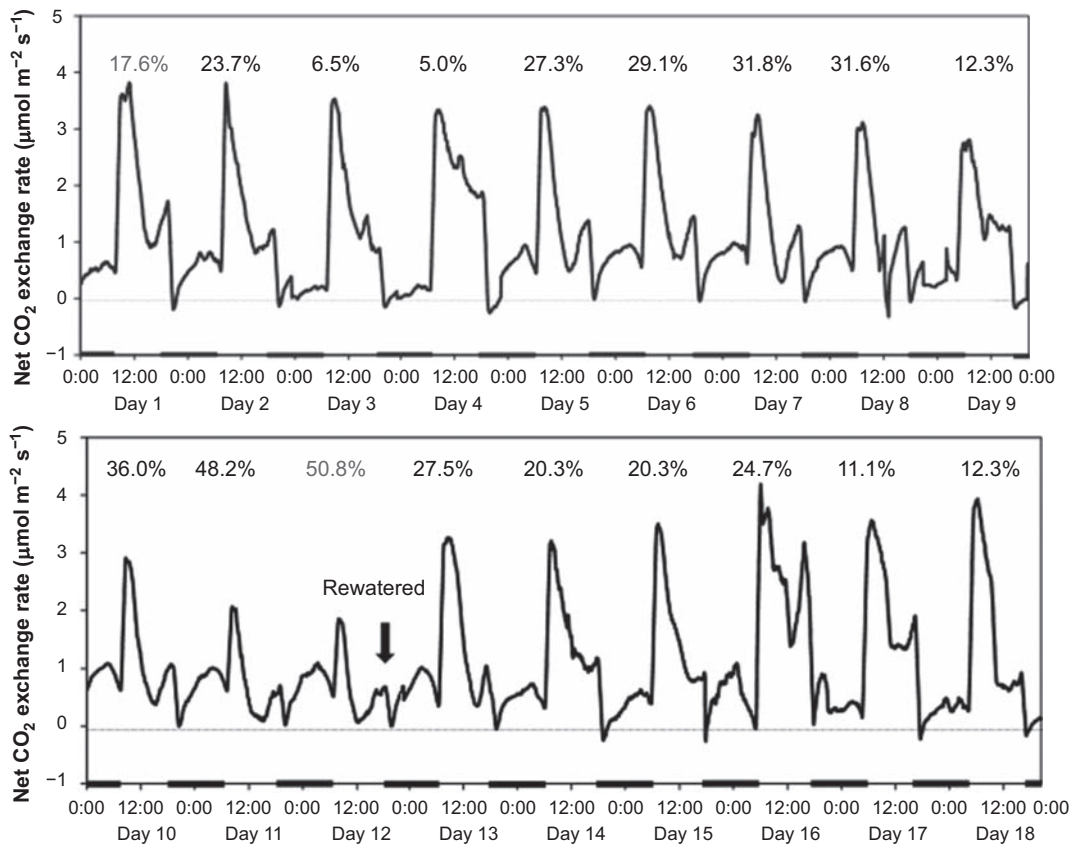


FIGURE 22.19

Time course of net CO₂ exchange rates and the percentages of net CO₂ exchange during the dark period to the daily amount of *D. officinale* in a PFAL for 18 days. Dark bars on the x-axis indicate the dark periods.

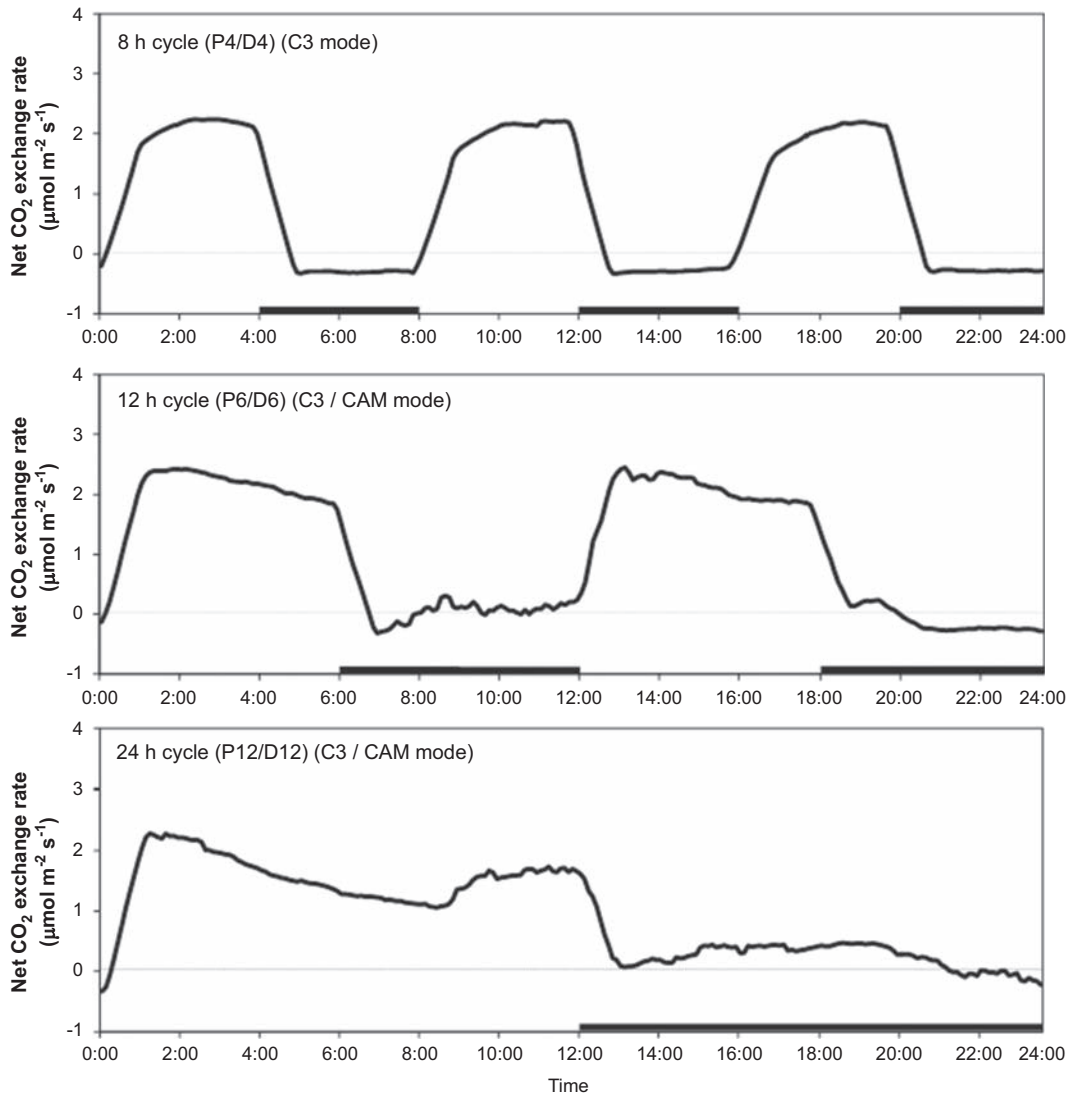
22.5 Blueberry

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Blueberries are perennial flowering plants from the genus *Vaccinium*; the fruits are proven to be rich in disease-fighting nutrients. Canada is the world's number-one producer and exporter of fresh and frozen wild blueberries, with exports valued at \$196 million in 2013. Blueberry cultivation is expanding rapidly throughout the world (Eck, 1988), which has led to an increased demand for planting stocks. Conventional propagation has limitations in meeting this increasing

**FIGURE 22.20**

Time course of net CO₂ exchange rates of *D. officinale* in 8 h (4 h photoperiod, 4 h dark period), 12 h (6 h photoperiod, 6 h dark period), and 24 h (12 h photoperiod and 12 h dark period) light-dark cycles. Dark bars on the x-axis indicate the dark periods.

demand as propagation by stem cuttings is slow and rooting is difficult (Nickerson, 1978). Lyrene (1978) observed only 7% rooting of stem cuttings, but 95% rooting of tissue culture-derived microcuttings. Consequently, micropropagation has become increasingly popular for rapid multiplication of virus-indexed cultivars (Wolfe et al., 1983). However, tissue culture is generally an expensive process (Dunstan and Turner, 1984; Kozai and Iwanami, 1987); therefore, innovative technology needs to be developed that can reduce the costs and make tissue culture more attractive to nursery operators. Much research has been conducted in recent years on the development of protocols for in vitro propagation of different varieties of blueberry plants (Brissette et al., 1990; Meiners et al., 2007).

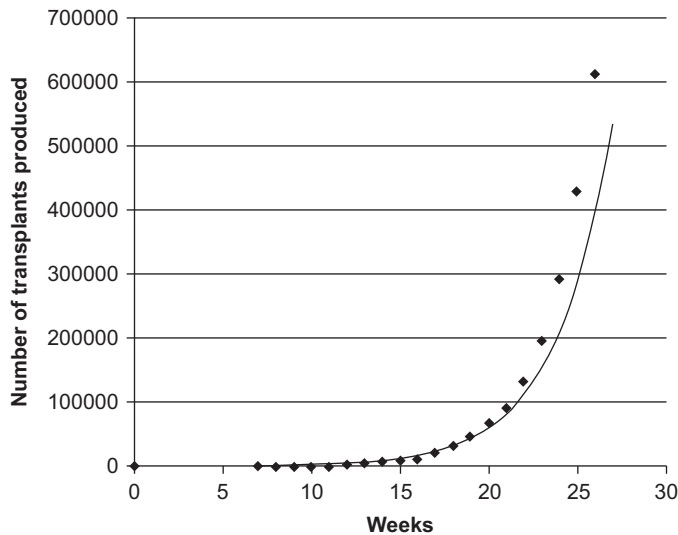
A closed controlled environment system has recently been described as an alternate method of plant propagation (Zobayed et al., 2005). Although the system has many benefits over the conventional method of greenhouse propagation (Kozai, 2005), it is still limited mostly to propagation through seeds. On the other hand, tissue culture-derived transplants have many advantages such as rapid, true-to-type, and disease-free transplant propagation with bushy appearance of the final plant products. In this chapter, a new method of transplant production using tissue culture-derived microcuttings of blueberry transplants (*Vaccinium corymbosum* “Duke”) under a closed controlled environment system is described. Microcuttings obtained in vitro were transplanted in 432-multicell trays filled with perlite (20%) and peat moss (80%) previously sterilized at 200°C for 3 h using a soil sterilizer (Gothic Arch Greenhouses, USA). Trays were placed under controlled environment conditions with a relative humidity of 90%; 16 h photoperiod with a light intensity (PPF) of $100 \mu\text{mol m}^{-2} \text{s}^{-1}$ for the first 7 days followed by $200 \mu\text{mol m}^{-2} \text{s}^{-1}$. The room temperature was maintained at 23°C throughout the dark and light periods and CO₂ concentration was elevated at 1500 ppm. From day 15, nutrient solution containing N:P:K (ratio of 20:20:20) added with some growth regulators (combination of auxin and cytokinin) was circulated around the root system for 10 min every 3 days using an even-flow hydroponic system.

A well-established root system developed within 4 weeks of transplanting (Fig. 22.21); on week 5 the tips of each transplant were extracted and replanted following the same procedure as described above. These transplants usually take about 5 weeks to establish and the tips were cut and replanted again from both old and new batches. This procedure can be continued and within 6 months approximately one million transplants can be obtained from 2000 tissue culture-derived shoot cuttings in a floor area of 1800 sq ft (eight layers of shelves) (Fig. 22.22). The multiplication ratio (number of

FIGURE 22.21

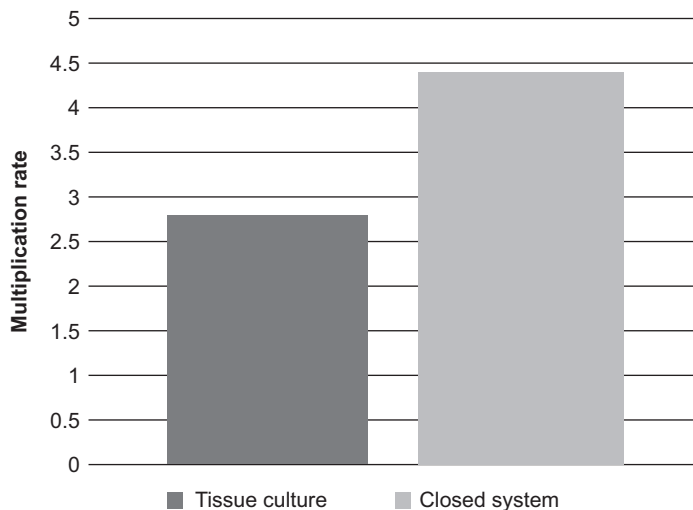
Blueberry transplants growing under a closed controlled environment system.



**FIGURE 22.22**

Number of transplants in a closed controlled environment system (an exponential growth curve).

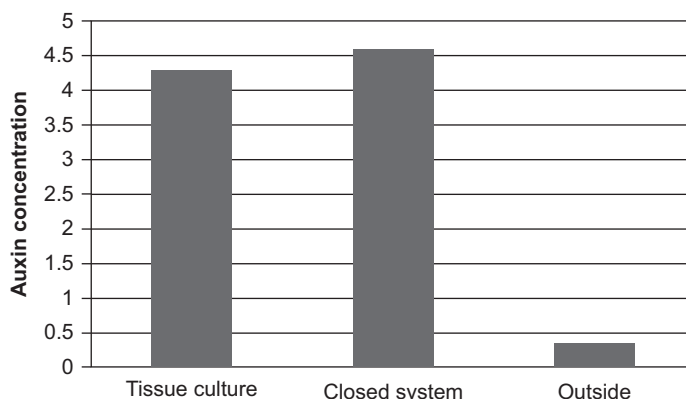
transplants produced from each mother plant in a month) of the plants through this procedure is higher than that by tissue culture (Fig. 22.23). Transplants were eventually moved to a greenhouse for further establishment. Biochemical analysis showed that these plants have similar auxin (indole-3-acetic acid) concentration in their shoot tissues compared with that of the tissue culture-derived plants directly established in a greenhouse (Fig. 22.24). Their morphological appearance (bushy) and growth after transplanting under greenhouse conditions were similar to tissue culture-derived plants.

**FIGURE 22.23**

Multiplication ratio of blueberry plants grown under tissue culture and closed control environment system.

FIGURE 22.24

Auxin concentration ($\mu\text{g/g}$ dry mass) of blueberry plant shoot tissues obtained from tissue culture-derived plants, transplants grown under closed controlled environment system and from field-derived plants (collected on May 2013; Lynden, WA 98,264, USA).



The advantages of this system of propagation are:

1. production of high-quality transplants,
2. uniform growth of transplants under uniformly controlled environments,
3. grown in a protected area free from pests, insects, and pathogens and thus transplants are disease-free,
4. virus-free transplant propagation as the initial microcuttings are originated through tissue culture,
5. no disturbance by outside weather, enabling year-round production,
6. low production cost.

The low production cost can be explained as follows:

- (1) the very high productivity per unit floor area per year, mainly due to the use of multilayered shelves (eight shelves),
- (2) a high planting density per unit tray area,
- (3) a high percentage of salable transplants ($>95\%$), and shorter production period (30%–70% compared with greenhouse),
- (4) higher utilization efficiencies of water, CO_2 , and fertilizers than a greenhouse mainly due to the minimized ventilation and recycling of water,
- (5) virtually no heating cost even in the winter because of its thermally insulated structure,
- (6) lower labor cost due to the smaller floor area, worker-friendly shelves, and comfortable working environment,
- (7) easier control of plant development such as stem elongation, flower bud initiation, bolting, and root formation (Kozai et al., 1998, 1999, 2000a,b,c, 2004; Kozai, 1998),
- (8) unlike the tissue culture system, there is no need for any special medium preparation, sterilization of tools and medium, and laminar flow (HEPA filtered air flow),
- (9) rooting percentage in this system is almost 100%.

Commercial application of the closed controlled environment system for blueberry transplant propagation requires the development of additional protocols for optimum production. Potential approaches include manipulation of many physical and chemical growth conditions such as light,

temperature, and nutrition, which influence the multiplication ratio and growth of blueberry transplants. This technology is likely to play a significant role in the production of high-quality blueberry transplants in the near future.

22.6 Propagation and production of strawberry transplants

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22.6.1 Vegetative propagation of strawberry

Strawberries are widely appreciated for its characteristic aroma, bright red color, juicy texture, and balanced sweetness and sourness. It is cultivated worldwide, including in China, the United States, Mexico, Spain, Japan, and Korea. Strawberries are mainly grown in open fields in the United States and European countries. On the other hand, in northeast Asian countries, almost all strawberry production is greenhouse based. From the past, the cultivation area and production of strawberries have steadily increased and its annual market value will be over \$20 billion (USD) in 2020 (FAOSTAT, 2018).

The most cultivated strawberry is *Fragaria x ananassa* Duch that is an octoploid ($2n = 8x = 56$) and interspecific hybrid between the wild species *F. chiloensis* L. ($2n = 8x = 56$) and *F. virginiana* Duch (Darrow, 1966). In addition to its polyploidy, allogamous behavior in *F. x ananassa* contributes further complexity to the genome structure. As intraspecific crosses have been extensively used to obtain new cultivars with improved agronomic traits, seed propagation has become unreliable in strawberry production, while limited numbers of seed-propagated cultivars, mainly ever-bearing, and are commercially available using their near isogenic lines.

Most commercial strawberry cultivars are reproduced asexually, mainly using vegetative cuttings made by burying the vegetative stolons, called runners. The runners are this plants' means of vegetative propagation, as runner plants arise from the crown during long days with warm temperatures, beginning in late spring and continuing until autumn (Kirsten, 2013). After the development of numerous lateral roots, the runner plants become independent and are cut free from the mother plants.

Strawberry nurseries produce runner plants rooted in substrate in a cell tray (called plug transplants) or a small plastic pot to be supplied as transplants to growers. Some of the advantages of strawberry plug transplants are a reduction in pesticide requirement and soil-borne diseases, ease of transplanting, reduced water requirement, and improved plant survival (Durner et al., 2002). The continual growing and cutting of plants from previous ones is the main job of the commercial strawberry nursery. Propagules are transplanted in greenhouses at the end of March for early forcing culture and at the end of April for semiforcing culture to grow into mother plants for producing transplants needed around the middle of September and middle of October, respectively, in the cases of Korea and Japan.

22.6.2 Licensing and certification

To meet increasing customer demand for fruit quality and year-round supply and to adapt to changes in local climates and progress of production technologies, new strawberry cultivars have been

continuously bred. These new cultivars are protected by plant patents in the USA and Canada, while the most common form of intellectual property protection in many parts of the world is UPOV (Union for the Protection of New Varieties of Plants), which specifies the rights of compliant plant breeders. Forms of licensing varieties and systems for collecting royalties differ from country to country. In the USA and Canada, varieties are licensed on a nonexclusive basis directly to plant nurseries. In the EU, Japan, and Korea on the other hand, the licensing program relies on business partners including private enterprises, nonprofit organizations, and local government bodies with exclusive rights within a defined territory.

The licensed organizations have their own systems for the production, propagation, and distribution of disease-tested stocks. In terms of certified strawberry materials, there are several different grading systems, e.g., nuclear stock, foundation 1 stock, foundation 2 stock, super elite stock, elite stock, and A grade stock under the UK system; nuclear stock (SEE), propagation stock I (SE), propagation stock II (EE), and certified stock (E) under the Dutch system; and nuclear transplant, elite transplant, prebasic transplant, and basic transplant under the Korean system, and so on (FERA, 2006). The highest-grade transplants are grown under very strict conditions, are propagated under careful control, and receive field inspections for major pathogenic viruses and nematodes. To eliminate viruses and other pathogens and to reinvigorate strawberry plants for increased runner production, tissue culture is used (Rancillac and Nourrisseau, 1989). One meristem plant can bear 300–800 daughter plants in one season in a screened greenhouse (FPS, 2008). However, micropropagation of strawberries is not widely used in many countries because of problems with variant types, especially a hyperflowering trait, as documented by Jemmali et al. (1995).

22.6.3 Plug transplants

Plug transplants are small containerized plants produced from runner tips, which are an alternative to conventional field-grown strawberry transplants (Durner et al., 2002). These are grown in greenhouses and high tunnels in less time than field-produced bare-root transplants. Uses for plug transplants have dramatically increased in recent years, especially in Korea, Japan, and China where most strawberries are cultivated in greenhouses. This is because the plug transplants afford flexible transplanting dates, the opportunity for mechanical transplanting, and allow greater water utilization efficiency for transplant establishment compared to fresh bare-root plants.

Technology for producing plug transplants has progressed, resulting in improved cost efficiency, uniformity, and elimination of viruses. Further well-coordinated efforts among horticulturists, engineers, and industry could lead to the development of more efficient and useful production systems for strawberry plug transplants.

22.6.4 Transplant production in a PFAL

The novel propagation method for producing strawberry plug transplants in a PFAL developed by Chun et al. (2012) differs from conventional methods in: (1) small size of propagules, (2) high plant density, (3) early fixation of unrooted runner tips, (4) use of generated runner plants as propagules for subsequent propagation cycles, (5) fast propagation cycle, (6) year-round propagation, (7) uniformity of propagules, runner plants, and harvested plug transplants, and (8) simultaneous growth of propagules to attain a sufficient size of plug transplants for shipment or cold storage. Fig. 22.25 shows a schematic diagram of this propagation method.

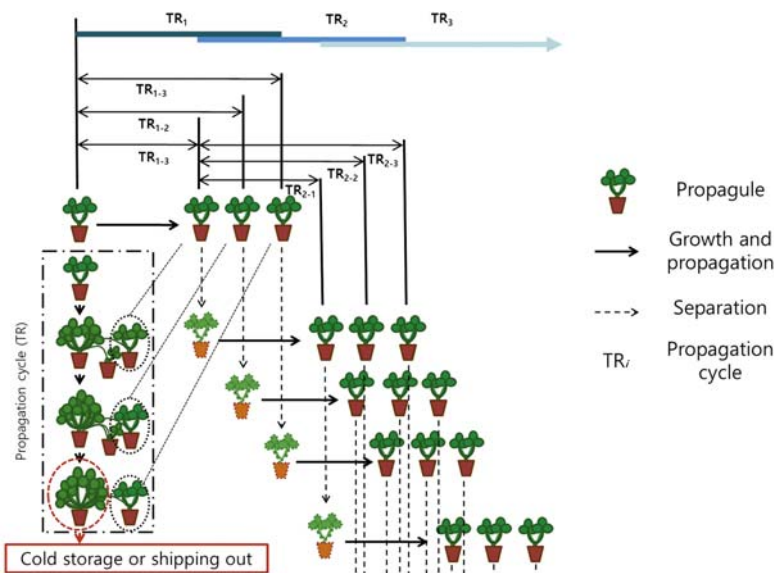


FIGURE 22.25

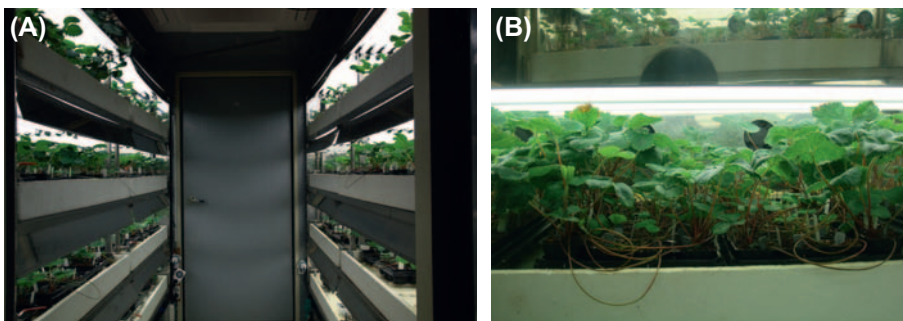
Schematic diagram of a novel propagation method for producing rooted plug transplants of strawberry in a PFAL developed by Chun et al. (2012). TR_i is the propagation cycle of the i -th generation.

Configuration of S-PFAL

S-PFAL (a PFAL for strawberry transplant production, Fig. 22.26A and B) basically has the same structural elements as the PFAL reported by Kozai (2013b): (1) thermally insulated warehouse-like structure, (2) multiple racks (30–40 cm between racks vertically) equipped with lighting devices, (3) air conditioning facilities, (4) CO_2 delivery system, (5) fans for circulating room air, and (6) nutrient solution delivery system. The configuration of an S-PFAL is also similar to a practical commercial system initially developed for seedling production.

Environmental control

Chun et al. (2003) found that not only the growth of mother plants but also the formation of runners and growth of runner plants of “Hokowase” were promoted under elevated CO_2 concentration (800–1200 $mg \cdot L^{-1}$). Kim et al. (2010) reported that the propagation rate of “Maehyang” cultivar increased as PPF increased (220–280 $\mu mol \cdot m^{-2} \cdot s^{-1}$) in an S-PFAL. Long day condition (e.g., photoperiod of 16 $h \cdot d^{-1}$) and relatively warm air temperature (e.g., photo-/dark periods of 28/24°C) promote runner formation, runner elongation, and initiation and growth of runner tips and runner plants, and consequently increase the rate of propagation. Both propagules and runner plants are subirrigated with Yamazaki nutrient solution for strawberry (2 N, 1.5 P, 3 K, 2 Ca, 1 Mg, and 1 S $me \cdot L^{-1}$; 0.7 $mS \cdot cm^{-1}$) for 10 min, twice a day.

**FIGURE 22.26**

S-PFAL for production of strawberry plug transplants (A) and propagules and runner plants growing on each rack (B).

Small propagules with high planting density

Mother plants in conventional propagation methods in greenhouses or nursery fields are usually too big to be contained in a rack (30–40 cm high) of an S-PFAL. In the present propagation method, the initial propagules were selected from runner plants of virus-free nuclear stocks. Small propagules (Fig. 22.27A) that had a crown diameter of 5 mm and two leaves are used. Each of six propagules is transplanted on a cell of one side row of a 32-cell plastic tray. The distance between two adjacent propagules is 5.9 cm and each cell is filled with 125 mL of growing medium (Fig. 22.27B), resulting in a planting density of 44.4 propagules/m².

Fixing of runner tips

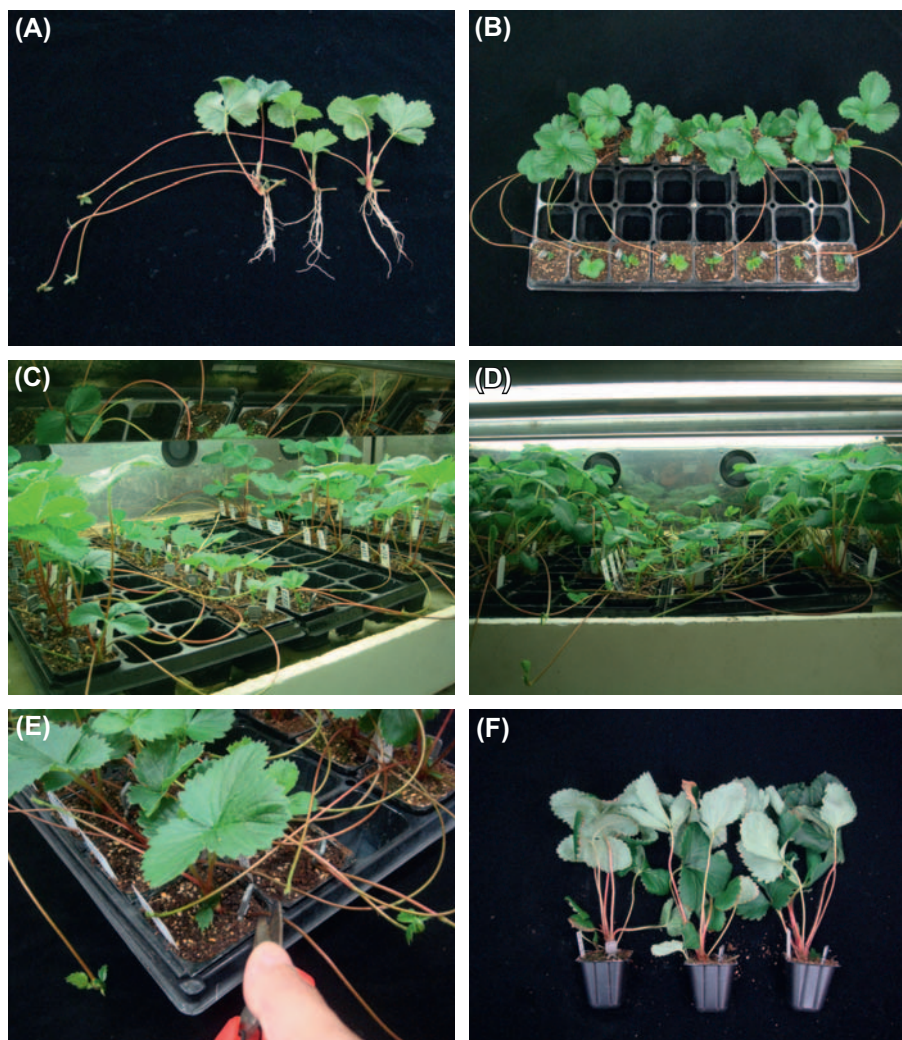
Runners from propagules are placed on the medium surface of other cells of the tray and runner tips are fixed 10–12 days after runner initiation using U-shaped staples (Fig. 22.27C). Within 2 days after fixation, new roots of 2–3 cm in length develop and an adventitious root zone is consequently established from the bottom of runner tips. In one propagation cycle, three runner tips from a propagule are fixed in sequence (Fig. 22.27D).

Separation of runner plants

Three runner plants are sequentially separated from propagules by snipping the runners when their size reached the same size as initial propagules (Fig. 22.27E). When they are separated, the crown diameter is about 5 mm and the leaf number is about two. The plants are used as propagules in the subsequent propagation cycle.

Simultaneous growth of propagules

When the third runner plant is separated from propagules, the crown diameter and leaf number of initial propagules become about 12 mm and 7, respectively (Fig. 22.27F), which is similar to the size of stocks used for conventional propagation in greenhouses and nursery fields. It is also similar to the size of transplants used for soilless culture. Hence, they can be harvested as rooted plug transplants and shipped out. After short and simple acclimatization they can be transplanted for fruit harvest, yielding advantages in dormancy break and promotion of flowering. They can also be stored at –2°C since they

**FIGURE 22.27**

Smaller propagules (A) are transplanted on plastic plug trays (B) to be cultivated for producing rooted plug transplants. Using U-shaped staples (C) three runner tips from a propagule are fixed in sequence (D) and the rooted runner plants are separated when they reach the same size as initial propagules (E) to be used as propagules in the next propagation cycle. At the end of each propagation cycle, the initial propagules are harvested for shipment or cold storage, of which crown diameter and leaf number are similar to those of stocks used in conventional propagation methods (F).

are continuously produced year-round in the S-PFAL, while stocks for propagation and transplants for cultivation are needed only at certain times of the year.

LED lighting for S-PFAL

In the first generation of S-PFAL fluorescent lamps were used as the sole lighting source. As LEDs became an alternative of fluorescent lamps because of high efficiency, long lifetime, and spectrum controllability, white LEDs are now installed in the new S-PFAL. A recent study presents that the mint-white LEDs having a peak spectrum at 547 nm and 7250°K of correlated color temperature (CCT) with a relatively high proportion of green and blue lights promoting vegetative growth and the runner formation of propagules (Lee, 2019). The propagation rate further increases when the blue LEDs (454 nm of a peak spectrum) are added to the mint-white LEDs with 2:8 ratio resulting in about 12,200K of CCT. Recently a full line-up with highly efficient white LED packages were released for horticultural uses including the S-PFAL (Samsung Electronics Co., Ltd., 2019).

Productivity of S-PFAL

The productivity of this new propagation method in an S-PFAL can be evaluated from the cumulative number of runner plants produced. Under optimized culture conditions determined from a series of experiments as described above, Chun et al. (2012) produced 3497 runner plants in 365 days, starting the propagation process with nine propagules and a cultivation area of 3.6 m² in an S-PFAL with fluorescent lamps, which is about 110–140 times greater than that by conventional propagation methods. In this trial, the maximum number of propagules cultivated at the same time was 160, and the cumulative number of runner plants produced increased exponentially until it reached this number, and then increased linearly after exceeding the maximum capacity. Simulation results showed that the annual cumulative number of runner plants produced could be increased to 19,103 and 36,345 if the cultivation area were 18 and 36 m², respectively, under the optimum lighting spectrum with mint-white and blue LEDs, as described above.

22.6.5 Application of S-PFAL in Korea

The strawberry cultivation area in Korea is 5907 ha and its yield was 209,000 tons in 2017. The Korean strawberry industry was highly dependent on foreign cultivars and the domestic cultivars accounted for less than 4% of the total cultivation area in 2003. However, as new domestic cultivars with high fruit quality have been sequentially bred and introduced, this percentage dramatically increased to 94.5% in 2018.

Transplant production of strawberries is slow, laborious, and expensive with many limitations. About 25–30 runner plants per mother plant can be propagated in a year with conventional propagation methods. About one billion strawberry rooted plug transplants are needed every year and it takes 5–6 years to diffuse the transplants of newly developed cultivars to Korean growers.

Several S-PFAL using the novel propagation method have been built on a trial basis at national and provincial research agencies where major domestic cultivars are bred and nuclear stocks are maintained. The trials were satisfactory, and so scaling up is currently being reviewed for propagating mainly elite transplants in the Korean national propagation program.

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Photoautotrophic micropropagation

23

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23.1 Introduction

Photoautotrophic micropropagation (PAM) narrowly refers to the propagation and growth of explants or plants under disease-free conditions on medium containing no supplemental organic components as nutrients. In PAM or sugar-free medium micropropagation, chlorophyllous explants having photosynthetic ability are used to enhance their photoautotrophic growth. Environmental factors such as light intensity and carbon dioxide concentration need to be properly controlled for promoting photosynthesis of explants and/or plants. Photoautotrophic micropropagation, which improves both the in vitro aerial and root zone environments, significantly promotes the growth of in vitro plants, increases the multiplication rate, and thus shortens the multiplication period of the in vitro stage. Moreover, in vitro plants grown under photoautotrophic conditions show better acclimatization with higher survival rate during the ex vitro stage. As plants, by nature, are considered as photoautotrophic organisms by using inorganic materials existing in the environment to produce carbohydrates for their own need via photosynthetic activity, PAM has recently become a worthy method in commercial plant production in a controlled environment. This chapter reviews the special features of PAM and its practical application over the last decade, and the potential for scaling up large culture vessels to aseptic culture rooms for closed transplant production systems.

23.2 Development of PAM

Intensive studies on the PAM method started in the late 1980s at Chiba University, Japan, with several experiments on environmental factors surrounding in vitro plants in small vessels, such as CO₂ concentration, photosynthetic photon flux density (PPFD), photo- and dark periods, etc. All findings revealed a high net photosynthetic rate of in vitro plants cultured on media containing only inorganic components when the in vitro environment is properly controlled.

There have been more than 100 articles reporting successful PAM for more than 50 plant species (Kozai et al., 2005), and there have been about eight review papers on this new method (Kozai, 1991, 2010; Jeong et al., 1995; Kubota et al., 1997; Kozai and Nguyen, 2003; Zobayed et al., 2004; Kozai and

Xiao, 2005; Xiao et al., 2011). There have also been four books containing chapters on PAM (Kurata and Kozai, 1992; Aitken-Christie et al., 1995; Kubota and Chun, 2000; Kozai et al., 2005). PAM was also the focus of one symposium (Kozai et al., 1995).

These publications stated that most chlorophyllous explants/plants in vitro, including somatic embryos at the cotyledonary stage, are able to grow photoautotrophically, and that the low or negative net photosynthetic rate of plants cultured photomixotrophically is due to not only poor photosynthetic ability, but also the low CO₂ concentration in the airtight culture vessel during the photoperiod. Furthermore, it has been proved that the photoautotrophic growth of many plant species can be significantly promoted by increasing the CO₂ concentration and light intensity in the vessel, by decreasing the relative humidity in the vessel, and by using a fibrous or porous supporting material with high air porosity instead of gelling agents such as agar.

These studies have shown that for successful PAM, an understanding of the in vitro environment and basic theories of environmental control is essential. From our own experience, another important aspect for successful application is a physio-ecological knowledge of plant species. To enhance photosynthesis of in vitro plants, it is necessary to understand the status of the in vitro environment inside the culture vessel and know how to create optimum environmental conditions for maximizing in vitro plant photosynthetic growth. Without good knowledge of the in vitro environment, the interaction between plants and the in vitro (and ex vitro) environments and also the interaction between the environment and plant genotype, the PAM method is difficult to apply.

23.3 Advantages and disadvantages of PAM for growth enhancement of in vitro plants

PAM has many advantages over conventional (photomixotrophic) micropropagation using sugar-containing medium with respect to both the biological aspects of in vitro plants and engineering aspects. Biological advantages include: (1) promotion of growth and photosynthesis of in vitro plants; (2) prevention of morphological and physiological disorders; (3) decrease in microbial contamination inside the culture vessel; (4) shortening of the in vitro plant multiplication cycle; and (5) high survival rate of in vitro plants when transferred to an ex vitro environment. Engineering advantages include: (1) simplification of the micropropagation system; (2) flexibility in the design of the culture vessel for large-scale in vitro plant production; (3) year-round increase in production yield per unit floor area; (4) reduction of labor cost; and (5) easier automation of the culture system.

However, PAM also has disadvantages such as: (1) knowledge required of the physical in vitro environment; (2) higher costs for CO₂ enrichment or use of gas-permeable filter discs to increase CO₂ concentration in the vessels, lighting and cooling; and (3) limited application to multiplication system using multishoots or plants having a C₄ or CAM photosynthesis pathway.

In PAM, PPFD and CO₂ concentration during the photoperiod play the most important roles. Since increasing PPFD alone cannot raise the net photosynthetic rate for in vitro plants at their CO₂ compensation point, the CO₂ concentration in the vessel needs to be increased to at least 400 μmol mol⁻¹ (standard atmospheric CO₂ concentration in the culture vessel, not in the culture room) either by natural or forced ventilation.

23.4 Natural ventilation system using different types of small culture vessels

The natural ventilation method is mainly described as an air exchange (CO_2 and water vapor), caused by the difference in partial pressure in water vapor and CO_2 gas and the difference in air pressure between inside and outside the vessel caused by the air current surrounding the vessel. One simple way to enhance the natural ventilation of a vessel is to use lids with gas-permeable filters, or to use vessels with improved ventilation properties. Therefore, the vessel ventilation rate or number of air exchanges (N) will be increased in accordance with the number of microporous gas filter discs attached to the vessel. In the natural ventilation method, by attaching one, two and three Millipore filter discs (10 mm in diameter each) on the vessel lid or sidewalls, the CO_2 concentration inside a Magenta GA-7 box-type vessel containing in vitro plants reaches about 150, 200, and 250 $\mu\text{mol mol}^{-1}$, respectively, during the photoperiod when the CO_2 concentration in the culture room is maintained at 350–400 $\mu\text{mol mol}^{-1}$. By increasing the ventilation of the culture vessel, on the other hand, the ethylene concentration in airtight vessels can also be reduced, which in turn avoids the adverse effects of ethylene on plant development, such as shoot regeneration, leaf expansion, and shoot growth (Jackson et al., 1991; Biddington, 1992).

The benefits of using gas-permeable film or discs for increasing the vessel ventilation rate, plant photosynthesis, and growth have been shown by Kozai et al. (1988) in potatoes, Kozai and Iwanami (1988) in carnation, Nguyen et al. (1999) in coffee, Cui et al. (2000) and Kubota and Kozai (2001) in tomato, Nguyen and Kozai (2001) in banana (*Musa* spp.), Lucchesini et al. (2001) in myrtle (*Myrtus communis* L.), Xiao et al. (2003) in sugarcane, Couceiro et al. (2006a) in St. John's wort (*Hypericum perforatum*), Xiao and Kozai (2006) in statice, Zhang et al. (2009) in *Momordica grosvenori*, Martins et al. (2015) in *Billbergia zebrina*, Tang et al. (2015) in male chili pepper plants (*Capsicum* sp.), Hoang et al. (2017) in *Wasabia japonica* Matsumura and by many other authors. More than 10 species of woody plants, such as *Thyrsostachys siamensis*, *Gmelina arborea*, *Coffea arabusta*, *Azadirachta indica*, *Paulownia fortunei*, *Acacia*, *Eucalyptus*, *Macadamia*, papaya, chestnut, rubber tree, etc., were also proved to have greater growth on sugar-free medium in ventilated vessels than on sugar-containing medium in airtight vessels (Nguyen and Kozai, 2005; Cha-um et al., 2011; Teixeira da Silva, 2014; Vidal et al., 2017; Tisarum et al., 2018). Simulations for estimating the CO_2 concentration inside the culture vessel (C_i), net photosynthetic rate (P_n) of in vitro plants and increase in plant dry weight as functions of N, PPFD, and photoperiod were also conducted intensively by Niu et al. (1996, 1997).

When cultured in Magenta vessels on two supporting materials, Gelrite (G) or Florialite (F), under ambient CO_2 concentration (400 $\mu\text{mol mol}^{-1}$) and PPFD of 100 $\mu\text{mol m}^{-2} \text{s}^{-1}$, in vitro strawberry (*Fragaria* × *ananassa* Duch.) plants showed an increase in P_n over time under FG and FF treatments on sugar-free medium, as compared with SG and SF treatments on sugar-containing medium (see the caption of Fig. 23.1 for treatment codes), which stayed near the compensation point (Nguyen and Nguyen, 2008). After 15 days in the ex vitro stage, the survival percentage was the highest, 100%, in the FF treatment, and was the lowest, 85%, in the SG treatment (Fig. 23.1).

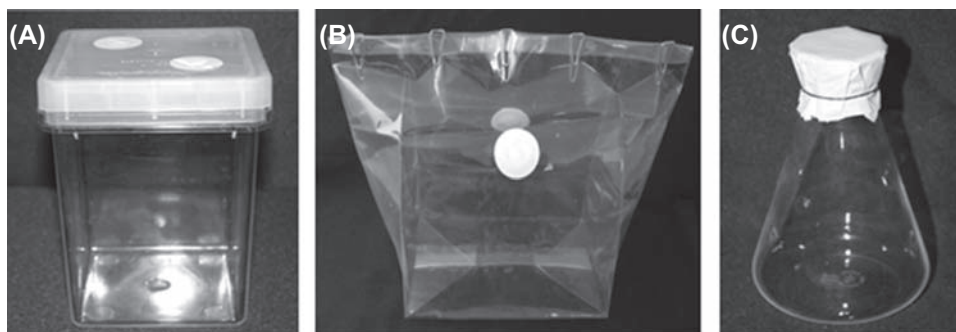
Nguyen et al. (2012) also proved the photoautotrophic growth of thyme plants (*Thymus vulgaris* L.) in ventilated Magenta vessels ($N = 3.9 \text{ h}^{-1}$) by using nodal cuttings. On day 35, thyme plants cultured on sugar-free medium under PPFD of 95 $\mu\text{mol m}^{-2} \text{s}^{-1}$ showed the greatest increase in fresh and dry weights, as well as the longest shoots and roots. P_n of in vitro thyme plants cultured on sugar-free

**FIGURE 23.1**

Strawberry in vitro plants as affected by different sucrose concentrations and supporting materials after 15 days in the ex vitro stage. For treatment codes, F or S on the left denotes sugar-free or sugar-containing medium, F or G on the right denotes Florialite or Gelrite used as supporting material.

medium was 10 times higher than those on sugar-containing medium under the same PPFD (2.6 vs. $0.23 \mu\text{mol h}^{-1}$ per plant).

There are numerous commercially available gas-permeable membrane and vessel systems with high ventilation characteristics, such as polycarbonate Magenta box-type vessels with Millipore gas-permeable filter discs as shown in Fig. 23.2A. However, gas-permeable filter discs are still costly, hindering the greater commercialization of photoautotrophic micropropagation. Flasks capped with thin, white paper or plastic (polypropylene) bag-type vessels with paper filter discs (1.3 cm in

**FIGURE 23.2**

Vessels often used in photoautotrophic micropropagation: (A) Magenta box-type vessel with Millipore filter discs fixed on each of the holes of the vessel cap; (B) plastic (polypropylene) bags with paper filter discs with the opening of the bag folded twice and fixed with five paper clips; (C) flasks capped with sterilized paper.

diameter) attached on the hole of the vessel sidewalls have been used for PAM in Vietnam recently because of their low cost (Fig. 23.2B and C). Nguyen et al. (2010a) proved that, on day 45, nodal cuttings of *Plectranthus amboinicus*, cultured on a sugar-free half-strength MS (Murashige and Skoog, 1962) medium inside plastic bag-type vessels (12 cm wide, 19 cm high, 8 cm deep at the bottom; air volume: 1.2 L when inflated with air) with two or four ventilated paper filter discs ($N = 4.2 \text{ h}^{-1}$ or 5.5 h^{-1} , respectively) grew much better than those cultured on sugar-containing medium inside bags without filter discs ($N = 0.7 \text{ h}^{-1}$). A high ventilation rate ($N = 5.5 \text{ h}^{-1}$) in accordance with high light intensity of $170 \mu\text{mol m}^{-2} \text{ s}^{-1}$, moreover, significantly increased fresh and dry weights of *P. amboinicus* in vitro plants (Nguyen et al., 2010a).

Plastic bag-type vessels ($V = 1 \text{ L}$ when inflated with air) with two ventilated paper filter discs were also used to prove the effect of light quality, produced by white, red, or blue fluorescent lamps, on the biomass accumulation of lavender (*Lavandula angustifolia*) plants cultured photoautotrophically (on MS medium with only mineral source) under ambient CO_2 concentration, PPFD of $140 \mu\text{mol m}^{-2} \text{ s}^{-1}$, and a photoperiod of 12 h d^{-1} . The number of primary roots and shoot length were the highest when lavender plants were cultured under red fluorescent lamps on day 42 (Fig. 23.3). However, under white fluorescent lamps, fresh and dry weights together with the number of secondary roots were significantly greater than those under blue or red fluorescent lamps (unpublished data).

The use of ventilated vessels obviously increases plant transpiration and medium evaporation, which is beneficial for plant growth because nutrient uptake of in vitro plants is also enhanced (Kozai, 2010). Explants, previously living in airtight vessels with poor cuticular wax layer formation and stomatal malfunction, may wilt for the first few days after being transplanted to the ventilated vessel. This phenomenon can be solved by covering all ventilated membranes with clear tape and reducing the PPFD at the culture shelf to a level equal to that of the previous culture ($30\text{--}50 \mu\text{mol m}^{-2} \text{ s}^{-1}$) for the first few days or a week. The tape needs to be removed and the PPFD should be raised gradually when

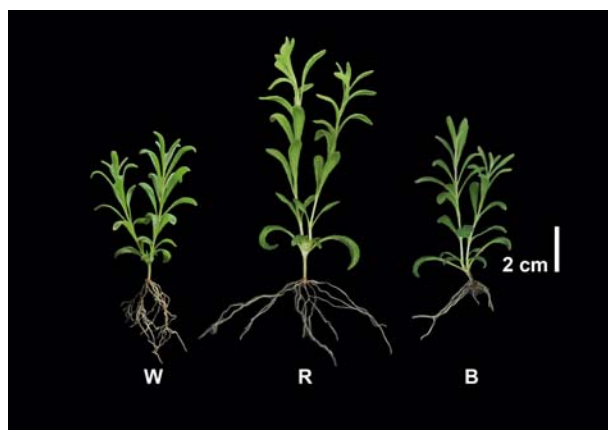


FIGURE 23.3

Lavender plants cultured photoautotrophically in plastic bags under different light qualities on day 42. For treatment codes, W, R, or B denote in vitro plants grown under white, red, or blue fluorescent lamps, respectively.

small new shoots and/or new roots appear. There is no wilting problem if explants are derived from the photoautotrophic condition. The use of a porous or fibrous substrate with dry substrate surface is obviously advantageous for promoting the root growth and is described in many publications. The transplanting of explants onto the medium in culture vessels or plastic bags will be easier to perform if the substrate is shaped into a cube block rather than a loose substrate (Kozai, 2010).

CO₂ in the ventilated vessel (C_{in}) in the natural ventilation method can be increased by enhancing the air diffusion (CO₂ and water vapor) through increasing the number of gas-permeable filters attached to the lid or sidewalls of the culture vessel. However, this cannot meet the plant demand for adequate CO₂ and will increase the cost of in vitro plants produced by this method (Kozai et al., 2005). Several publications showed beneficial effects of increasing carbon dioxide concentration higher than the ambient level on the growth of in vitro plants (e.g., Desjardins et al., 1988; Mosaleeyanon et al., 2004). By keeping the CO₂ concentration in the culture room (C_{out}) at around 1000 μmol mol⁻¹, C_{in} can be increased to about 500 μmol mol⁻¹; thus, P_n in the ventilated vessels is roughly 3.3 times greater in a CO₂-enriched culture room than in a CO₂-nonenriched culture room; whereas P_n is about 17 times greater in a CO₂-enriched culture room with ventilated vessels than in a CO₂-nonenriched culture room with nonventilated vessels (Kozai, 2010). This also explains why sucrose is needed for carbon assimilation in conventional micropropagation. Sha Valli Khan et al. (2003) showed that *P. fortunei* plants in vitro also developed a significantly large number of shoots under the photoautotrophic CO₂-enriched condition. Stomata of the leaf abaxial surface remained widely opened under the photomixotrophic condition when compared with those having a narrow opening under the photoautotrophic condition. High CO₂ levels can also improve the acclimation and growth rate of micropropagated plants when transferred to ex vitro conditions (Kapchina-Toteva et al., 2014). Kozai and Nguyen (2003) demonstrated that high CO₂ concentration (1600 μmol mol⁻¹) and high PPFD (250 μmol m⁻² s⁻¹) significantly enhanced the root initiation and normal root vascular development of *Paulownia* plants cultured photoautotrophically on a vermiculite-based medium for 28 days, and their growth continued increasing significantly during 15 days in the ex vitro stage. In another research, strawberry explants, under CO₂ of 1000 μmol mol⁻¹ and PPFD of 200 μmol m⁻² s⁻¹, developed shoots and roots that were twice as large as those under ambient CO₂ and PPFD of 100 μmol m⁻² s⁻¹ after 4 weeks of culture. The high level of CO₂ and PPFD in the in vitro stage continued improving the plant growth in the ex vitro stage (28 days) by producing the longest and greatest number of runners (Nguyen et al., 2008). Teixeira da Silva (2014) also showed that 1-month-old papaya plants cultured photoautotrophically under the CO₂ concentration of 3000 ppm could produce greater leaf number than control plants cultured on medium supplemented with 3% (w/v) sucrose.

Wu and Lin (2013) also proved that *Protea cynaroides* plants showed a significant increase in shoot growth when cultured on sugar-free medium but in the presence of some vitamins and plant growth substances under the CO₂-enriched condition. Particularly, the shoot dry weight of *P. cynaroides* plants cultured in 5000 and 10,000 μmol mol⁻¹ CO₂ were 2.1 and 4.2 times, respectively, higher than those cultured on sugar-containing medium in ambient CO₂ concentration.

For commercialization, C_{out} in the culture room can be controlled by using an infrared-type CO₂ controller connected with an injection unit of pure CO₂ gas in a container (Kozai et al., 1995). This controller is commonly used by growers for enriching CO₂ in greenhouses. Nearly 10,000 transplants can be produced using 1.5 kg of CO₂, provided the culture room is fairly airtight with little CO₂ escaping to the outside (Kozai, 2010). Methods and mass balance analysis of CO₂ enrichment in the culture room were described by Jeong et al. (1993).

In the natural ventilation system, C_{in} can be maintained at a higher level by increasing the carbon dioxide in the culture room. However, in large-scale production using numerous small culture vessels, C_{in} and other gas concentrations in the vessels having gas-permeable filter discs tend to be different from one another and are difficult to regulate during the culture period. Besides, it is not easy to obtain a high natural ventilation rate for a large vessel. This problem can be overcome by using forced ventilation.

23.5 Forced ventilation system for large culture vessels

In forced ventilation, C_{in} and air movement inside the vessel can be easily increased during the production process by flushing a particular gas mixture directly into the vessel, and the ventilation rate can be easily controlled using an airflow controller. C_{in} in a large vessel with an air volume of up to 100 L or greater can be maintained at around the ambient CO_2 of the culture room or gradually increased to a high level of over $1000 \mu\text{mol mol}^{-1}$ depending on the photosynthetic ability of in vitro plants. In this case, pure CO_2 or CO_2 diluted with air is directly injected into the vessel. When in vitro plants have high photosynthetic ability, large vessels with forced ventilation should be more effective with P_n increased when increasing the air current speed up to 50 mm s^{-1} and 100 mm s^{-1} compared with small vessels with natural ventilation (Kozai, 2010). Large culture vessels, which can be used for mass micropropagation, in different sizes and designs, have been used in photoautotrophic, forced ventilation of several plant species, such as *Eucalyptus* (Zobayed et al., 2000), coffee, yam (Nguyen et al., 2001, 2002), calla lily (Xiao and Kozai, 2004), *Dendrobium* (Nguyen et al., 2010b), *P. amboinicus* (Nguyen et al., 2011a), and European chestnut (Vidal et al., 2017). A simple configuration of a forced ventilation system is shown schematically in Fig. 23.4.

In vitro grapevines (*Vitis vinifera* var. Thompson seedless) grew much better, in terms of shoot length, number of unfolded leaves, and increased fresh and dry weights, in a forced ventilation system using polycarbonate vessels (Nalge Nunc Bio-Safe Carrier) compared with those in a natural

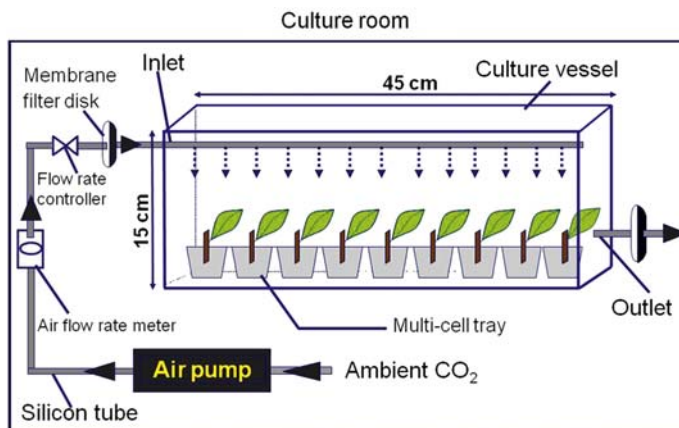
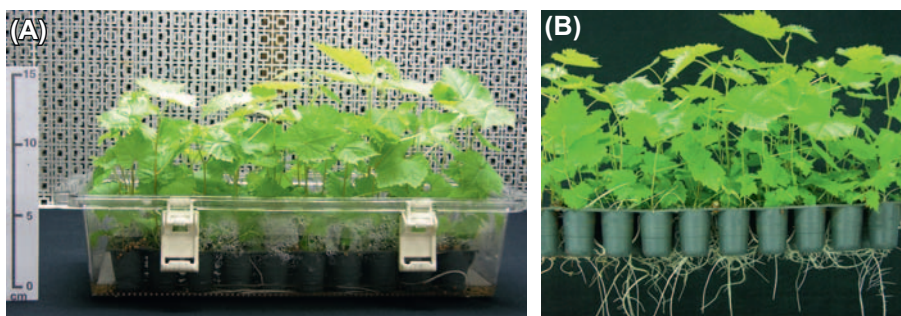


FIGURE 23.4

Schematic diagram of the forced ventilation system with polycarbonate vessel ($45 \times 25 \times 15 \text{ cm}$) used for photoautotrophic micropropagation at the Institute of Tropical Biology, Ho Chi Minh City, Vietnam.

**FIGURE 23.5**

Growth of in vitro grapevines (*Vitis vinifera* L. var. Thompson seedless) under forced ventilation system in a large vessel (Nalge Nunc Bio-Safe Carrier) containing 50 plants on day 35.

ventilation system using small Magenta vessels (Nguyen et al., 2011b). Moreover, the adventitious roots of grapevines developed a lot of lateral roots when the plants were grown on vermiculite, a porous supporting material (Fig. 23.5). *Kalopanax septemlobus* Nakai plants, cultured photoautotrophically in a forced ventilation system using large vessels ($V = 10$ L), produced more leaves, higher P_n in the in vitro stage and higher survival rate in the ex vitro stage when compared with those cultured conventionally (Park et al., 2011).

Several articles have proved that forced ventilation is more convenient and beneficial than natural ventilation when using large vessels for commercialization (Xiao and Kozai, 2004; Kozai et al., 2006). However, in a forced ventilation system, the increase in PPFD has a beneficial effect on enhancing growth and photosynthesis, provided that CO_2 concentration inside the vessel is also raised to meet the demand for carbon fixation of in vitro plants. Besides, it has been observed that an uneven spatial distribution of air current speed in a large vessel creates spatial variation in the growth of in vitro plants with forced ventilation (Kozai, 2010). Therefore, uniform air current speeds are essential for ensuring equal growth of plants in large vessels. This drawback can be overcome in a closed plant production system (Kozai, 2010).

23.6 Potential for secondary metabolite production of in vitro medicinal plants using photoautotrophic micropropagation

23.6.1 Introduction

As approximately 80% of the world's population uses herbal medicines, plant materials and extracted natural products are in high demand besides the demand for synthetic drug production; especially, the major components of synthetic drugs are derived from natural sources (Julsing et al., 2007). Plant tissue culture is widely used for the production of many medicinal plants, which features a constant production of identical germplasm from a limited stock material. Some defined plant-derived compounds, such as artemisinin, are widely produced in industrial processes in bioreactors. However, the medicinal properties of many plant species cannot be attributed to individually defined compounds, but rather are a consequence of the specific mixture of compounds found in the respective plant species

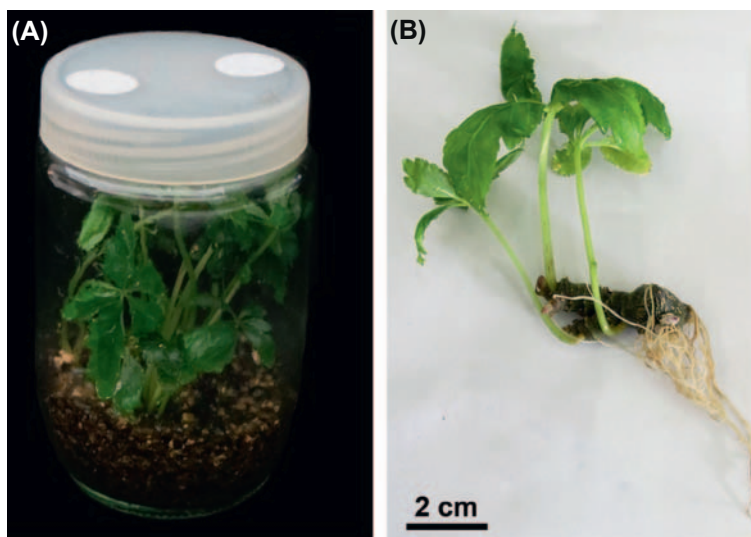
(Julsing et al., 2007). Moreover, the lack of consistency of the desired active metabolites in medicinal plants cultured in vitro is still a major problem (Kapchina-Toteva et al., 2014).

Sirvent et al. (2002) proved that medicinal plants grown in different environments show variations in the contents of their major secondary metabolites. Some experiments conducted under controlled conditions indicated that temperature and light might be major factors contributing to such effects (Canter et al., 2005). Zobayed and Saxena (2004) suggested that temperature, light intensity, and CO₂ concentration are not easily controlled in greenhouses and fields, causing variations in the yield of bioactive compounds and biomass of medicinal plants. However, these factors can be well adjusted when using micropropagation under a controlled environment. Therefore, feasible strategies for the commercial production of medicinal plants can be developed aiming to increase the yield of specific bioactive compounds by optimizing the environmental conditions. The major bioactive compounds of St. John's wort plants, namely hyperforin, pseudohypericin, and hypericin, were increased in plants grown photoautotrophically at high temperatures (Zobayed et al., 2005; Couceiro et al., 2006b). In vitro hardening of *Artemisia annua* plantlets cultured in liquid sugar-free medium with CO₂ enrichment was an effective procedure to enhance the production of artemisinin (Supaibulwattana et al., 2011). Saldanha et al. (2013) proved that sugar-free medium might increase the level of some secondary metabolites in *Pfaffia glomerata* when cultured in vitro under photoautotrophic conditions with nonenriched or enriched CO₂ (360 or 720 $\mu\text{mol mol}^{-1}$, respectively). A lack of sucrose in the culture medium increased 20-hydroxyecdysone levels, regardless of CO₂ levels. In another study, Pham et al. (2012) showed the positive effect of high CO₂ concentration (1200 $\mu\text{mol mol}^{-1}$) on the accumulation of two major lignans, phyllanthin and niranthin, in *P. amarus* plants cultured on sugar-free medium in a natural ventilation system after 45 days of culture. Light intensity and photoperiod also had effects on the accumulation of phyllanthin, hypophyllanthin, and niranthin when *P. amarus* plants were cultured photoautotrophically (Pham and Nguyen, 2014).

In vitro shoots bearing two open leaves of *Panax vietnamensis* Ha et Grushv., when cultured in two-hole Magenta vessels containing vermiculite-based sugar-free MS medium, could easily produce rhizomes and tuber roots in the in vitro stage (Fig. 23.6). In these organs, major ginsenosides of three groups: protopanaxadiol, protopanaxatriol, and ocotillol, including majonoside-R₂ (MR₂), existed at higher levels in the enriched CO₂ condition (1100 $\mu\text{mol mol}^{-1}$) compared with those in the non-enriched CO₂ condition on day 90 (unpublished data).

23.6.2 Scaling up a photoautotrophic micropropagation system to an aseptic culture room—a closed plant production system (CPPS)

The scaled-up forced ventilation system can be considered as an aseptic culture room, in which a large culture vessel contains many small sterilized trays. This kind of micropropagation system can also be considered as a transplant production system for growing small disease-free cuttings/seedlings or as a closed vegetative propagation system using artificial light. In this system, workers are not allowed to enter the culture room for handling the trays with plants or for regulating environmental devices in normal modes. Thus, automation must be used for both tray transportation and environmental control inside the culture room. Energy and mass exchanges between the inside and outside of the system can be minimized for maximizing water, CO₂, light, and other resource utilization efficiencies and for reducing electricity consumption (Kozai et al., 2005). The first CPPS was commercialized in Japan in 2004 and has since been used in more than 100 locations throughout Japan as of 2010 (Kozai, 2010).

**FIGURE 23.6**

In vitro plants of *Panax vietnamensis* cultured photoautotrophically from nodal cuttings: (A) on day 60 and (B) on day 180 with rhizome and tuber formation.

and more than 200 locations as of 2016. Thanks to improved control of the environment and pathogen invasion, transplants grown in CPPSs show more uniform, faster, pathogen-free growth than in a greenhouse.

23.7 Conclusion

Since the concept of PAM was developed more than 3 decades ago, many studies have been conducted on improving the in vitro environment and enhancing the growth and development of in vitro plants. Through these studies, practical experiences were added, such as gradually increasing the PPFD and CO₂ concentration in the microenvironment at the beginning of photoautotrophic application, or gradually decreasing sugar levels for one or two culture periods prior to the application. Although a large-scale PAM for commercialization has not been achieved worldwide, research ranging from the natural ventilation method using small culture vessels with gas-permeable filter discs to the forced ventilation method using large culture vessels has clearly proved the feasibility of scaling up the PAM system. This has led to the development of a new technology, the CPPS with artificial lighting, for high-quality transplant production. This system is not completely aseptic but is clean and pathogen-free. By combining the concepts of CPPS and PAM, a large number of high-quality transplants such as seedlings, small cuttings, and scions for grafting can be produced in a limited time with high energy and water use efficiency.

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Biological factor management

24

24.1 Introduction

Biological factor management is crucial in a plant factory with artificial lighting (PFALs) and other closed plant production systems (CPPSs) producing high-quality plants without using pesticides. However, there are few reports on biological factors such as algae, microorganisms, and pest insects. These biological factors may cause the degradation of plant quality and/or suppression of rapid plant growth as well as effects on human health. Much more research and development are required in this field.

The first section focuses on controlling algae growth, which is a critical maintenance task in PFAL crop production. The second section concerns food microbiological tests consisting of the environmental test and the quality test. Methods of measuring the total numbers of bacteria and fungi are described.

24.2 Controlling algae

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Controlling algae is a critical maintenance task in PFAL crop production. Wet surfaces in contact with nutrients and light can develop algae quickly. Examples include the upper surface of plant-growing substrate plugs/cubes used in hydroponics, gaps between floating panels over nutrient solution, the inside of plumbing made of light-transmitting material (tubing), and the nutrient reservoir exposed to light. Algae can house pests (such as fungus gnats) and therefore diseases and must be eliminated. Best practice is covering such surfaces with an opaque material to exclude light, but there are a few options to control algae chemically.

24.2.1 Hydrogen peroxide

The availability of a commercial product and its use may depend on government regulations, but if such a product containing stabilized hydrogen peroxide is available, it is a useful product for

controlling algae with minimal or no phytotoxicity. Some commercial products available in the United States are also registered for organic crop production use. The effective concentration may need to be carefully selected as potential phytotoxicity seems to be dependent on the different nutrient delivery systems. Substrate-based culture systems seem to have higher buffering capacity, whereas use of hydrogen peroxide product in deep flow technique (DFT) systems requires carefully selected concentration and frequency of application to avoid possible damage to the roots.

24.2.2 Ozonated water

A small system to generate ozonated water may be useful in PFALs. The ozone concentration should be carefully selected to be effective for algae control yet not cause phytotoxicity. [Graham et al. \(2012\)](#) reported that 3 mg/L was an upper limit for tomato seedlings grown in rockwool cubes. It is of interest that in some cases the application of ozonated water could improve overall plant productivity ([Graham et al., 2011](#)). Freshly made ozonated water could be sprayed around the problematic area developing algae as a control.

24.2.3 Chlorine

Use of a low dose of chlorine has been commercially practiced in hydroponic greenhouses. However, use of chlorine (or hypochlorous acid) for algae control in hydroponic systems of PFALs may need more research before further use is recommended. Caution may be needed as residual chlorine could form a highly phytotoxic compound, chloramine, when reacted with a low concentration of ammonium ions (NH_4^+) in the nutrient solution ([Date et al., 2005](#)). A typical symptom of chloramine phytotoxicity is root browning. Mixing sodium thiosulfate in the source water (tap water) at 2.5 mg/L is recommended to remove residual chlorine (S. Date, personal communication). However, when the system has many organic compounds (such as in the nutrient solution of recirculating systems or organic substrate-based culture systems), addition of chlorine may not be an issue, as organic matter would convert chlorine to chloride. [Date et al. \(2005\)](#) showed that lettuce growth was not inhibited in the range of 0–1 mg/L chlorine concentration when the nutrient solution did not contain $\text{NH}_4\text{--N}$. A small amount of NH_4^+ (5.2×10^{-3} mM) could inhibit lettuce growth when 0.5 mg/L chlorine was in the solution (and therefore forming chloramine) ([Date et al., 2005](#)). Given that tap water containing 1–2 mg/L of chlorine is typically used in PFALs in urban areas and that commercial hydroponic grade fertilizers contain trace amounts of $\text{NH}_4\text{--N}$, a cost-effective technology to remove NH_4^+ may need to be developed to allow effective usage of chlorine for algae control in PFALs.

24.2.4 Substrates

Leaf crop production in hydroponics starts with small substrate plugs to grow seedlings. Substrates with relatively high water-holding capacity (such as rockwool plugs) tend to have wet surfaces all the time and create favorable growing conditions for algae. In Asia, use of polyurethane foam as a substrate is common in hydroponics and polyurethane seems to have a relatively dry surface due to its low water-holding capacity. However, algae can still develop near the nutrient solution line inside the foam. Use of darker colored polyurethane foams that exclude light may better control algae.

24.3 Microorganism management

Miho Takashima

Methodologies for microbiological testing of food should be selected according to the purpose (Japan Food Research Laboratories (JFRL), 2013). The cultivation method takes time to obtain results, and requires experience and technology, but it is an international microbial testing method and currently the microbial testing standard. Meanwhile, the rapid method is a way to obtain results by abbreviating the culture method or replacing it in part or in whole with other methods (Igimi, 2013). Compared with conventional methods, the rapid method is one that enables quantitative determination regarding the presence of microorganisms and bacteria numbers in a short time. However, there are many methods with unconfirmed validity, and it is important to select and implement a methodology after confirming its rapidity, efficacy, sensitivity, reproducibility, and reliability.

24.3.1 Microbiological testing

This section focuses on microorganism control in a PFAL. Microorganism management in a plant factory is split into environment management and quality management. Fig. 24.1 shows the classifications for microbiological testing.

Environmental testing is largely divided into two methods. One is the testing of microorganisms in the air or attached to a surface, and the other is the testing of raw water and a culture solution (Fig. 24.1). In a PFAL, surface-attached microorganisms are considered to be the same as suspended ones, and in this instance, microbiological testing of raw water and culture solutions will also be considered as being included in the quality testing.

In quality testing, it is important to examine and understand the number of bacteria and fungi. These are the standards and indicators for microorganisms in food and the environment. It is also important to examine for contaminant indicator bacteria such as *Coliform* groups and *Staphylococcus aureus*, if necessary. The conventional plate count method is described in the following section.

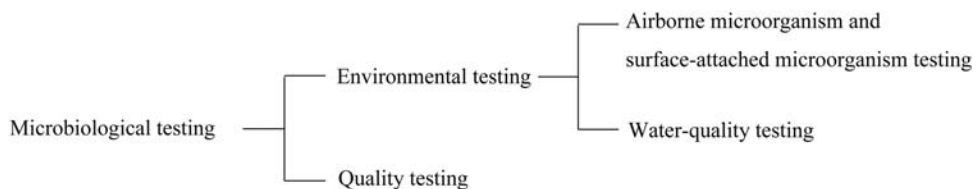


FIGURE 24.1

Classifications for microbiological testing.

24.3.2 Environmental testing—airborne microorganisms

Numerous microorganisms exist in the air, and are mainly bacteria, fungi, and viruses. A measurement methodology for viruses is yet to be established, as they are small and easily become inactive, which makes them difficult to culture and measure. Accordingly, measurement of airborne bacteria and fungi is what is conducted. Testing for bacteria means a viable bacteria count test, usually by testing using a standard agar medium. The bacteria count is used as a typical indicator of microorganism contamination (Japan Food Research Laboratories (JFRL), 2013). A viable bacteria count is determined after the most suitable incubation period, and displayed in terms of colony-forming units (CFUs) (Buttner et al., 1997). The concentration of airborne microorganisms (CFU per volume) is found by dividing the number of CFUs per sample by the volume of air sampled (Buttner et al., 1997). Testing for fungi means testing for molds and yeasts. Fungi are ubiquitous in nature and occasionally cause sickness in people (Yang and Johanning, 1997). Some reports also indicate that they have become a major problem in buildings where moisture control is poor or water intrusion is common (Yang and Johanning, 1997). Fungi such as molds and yeasts are factors that should be understood in PFALs, which always have highly humid environments.

Airborne microorganisms usually mean the bacteria (microorganisms) floating in the air, which attach to the surfaces of products or fall down to the ground. There are two methods for measuring airborne bacteria: testing for fallen bacteria and testing for airborne bacteria suspended in a fixed volume of air.

The effect of airborne microorganisms on humans and environments has been reported by Stetzenbach (1997), in a report in which he describes the adverse effects brought about in connection with airborne microorganisms (e.g., algae, bacteria, endotoxins, fungi, mycotoxins, protozoa, and viruses). According to the report, the environmental effect most airborne microorganisms have, except for algae and endotoxins, is to cause reductions in agricultural productivity. The report also describes occasional effects on human health (e.g., infections, allergic reactions).

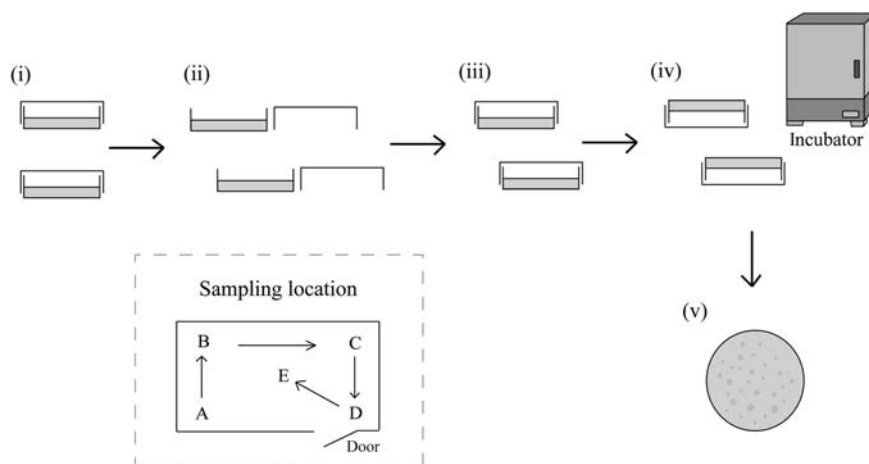
Measurement of the atmospheric environment evaluates quality, concentration, and quantity. In PFALs, it is important to generally know the overall total for bacteria and fungi counts. For this reason, two kinds of testing methodology are described in detail here.

24.3.3 Measurement of fallen bacteria using the plate method

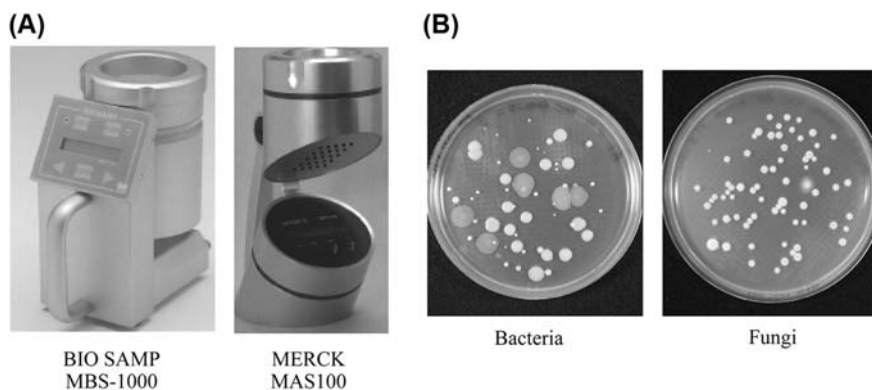
Sampling is conducted by opening the lid of a plate for a fixed period of time and allowing the culture medium to be freely exposed, after which the lid is closed and the culture medium inverted and incubated. The measurement methodology finds the number of developed colonies per plate after incubation, as illustrated in Fig. 24.2. Standard agar medium is used to test for bacteria, while a potato dextrose agar medium is used to test for fungi. This is the most widespread measurement methodology for airborne bacteria in Japan since it is extremely simple and can be carried out at low cost.

24.3.4 Measurement of airborne microorganisms

This is the typical method in Western countries, and one that has also received recognition in recent years in Japan (Yamazaki et al., 2001). The methodology is split into a number of methods based upon air sampling. As shown in Fig. 24.3, an impactor-type air sampler is used. This is recommended

**FIGURE 24.2**

Flowchart: Measuring microorganisms using the plate method. (i) Placement of two culture plates; (ii) the plates are placed at the measurement location with their lids left off—5 min for general bacteria, and 20 min for fungi; (iii) the plates have their lids put on; (iv) the plates are incubated at $35 \pm 1^\circ\text{C}$ for 48 ± 3 h for general bacteria, and $23 \pm 2^\circ\text{C}$ for 7 days for fungi; (v) the number of colonies is counted. The data are expressed as the number of colony-forming units (CFU) per unit time—CFU per 5 min for fallen bacteria, and CFU per 20 min for fungi. *Sample locations should be in accordance with the monitoring strategy. For example, as illustrated in steps A to D in the diagram, sampling locations are determined according to the flow of humans and objects.

**FIGURE 24.3**

Monitoring devices and examples of airborne microorganisms. (A) Air samplers from the hygiene environmental microorganism measuring instruments on the Marusan Pharma Biotech Corporation website; (B) measurement of PFAL airborne microorganisms at Sakakibara Heart Institute. An air sampler (BIO SAMP MBS-1000) was used. Pictures provided by SHARP.

by the International Organization for Standardization (ISO) and is commonly used to collect airborne microorganisms. Moreover, a variety of impactor-type samplers are commercially available (Buttner et al., 1997). Sampling methods need to consider air flow, and assess the average in the sampling area. Fig. 24.3 shows an example of measurement of bacteria and fungi. Not only does this method provide a quantitative evaluation, it also has the advantage of enabling the comparison of measurements under varying environmental conditions. The media used are the same as in the settle plate method.

24.3.5 Quality testing—testing for bacteria and fungi

The general procedure from sample preparation (Fig. 24.4A) to colony number determination (Fig. 24.4C) is shown in the diagram. Two kinds of tests are described in Fig. 24.4B, and are basically conducted in the same way but with one differing from the other in how the solution is added. The testing for bacteria is conducted using either of two methods, the coating method or the mixing method, with the coating method generally being used for fungi. Incubation is carried out using

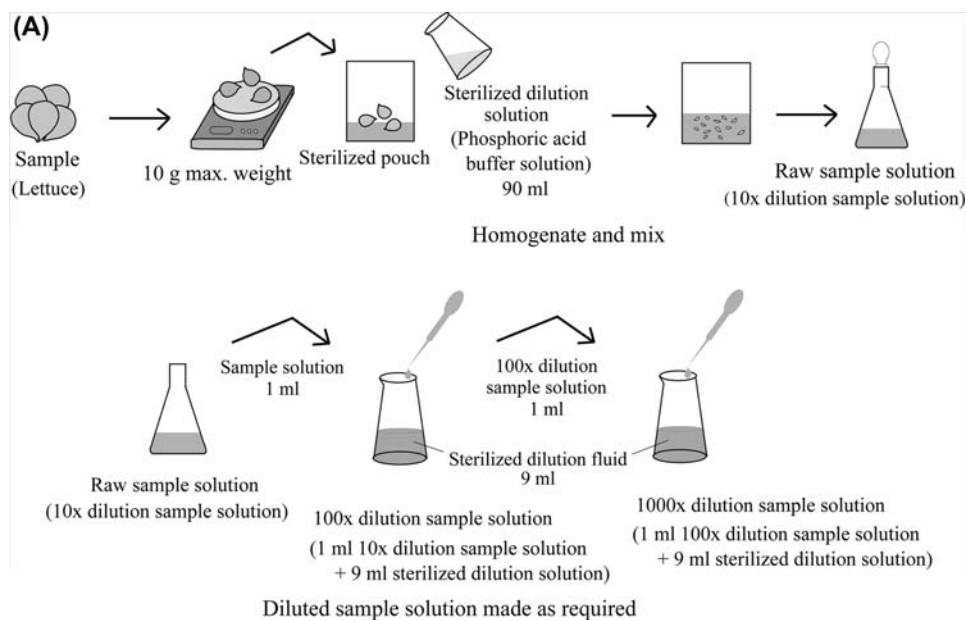


FIGURE 24.4

Outline of the testing procedure for bacteria and fungi. Sampling and testing were carried out as shown in (A)–(C): (A) sample preparation; (B) two testing methods; (C) counting of colony numbers. Plates with 30–300 colonies are selected for measurement. The average of the two plates is taken as the viable bacteria number. This is calculated from the total number of colonies on the two plates $\times 1/2 \times$ dilution factor. For example, at $100 \times$ dilution and with colony numbers of 168 and 183, the number of colony-forming units can be calculated using the following formula: $(168 + 183) \times 1/2 \times 100 = 17,550 = 1.755 \times 10^4 = 1.8 \times 10^4$ CFU/g.

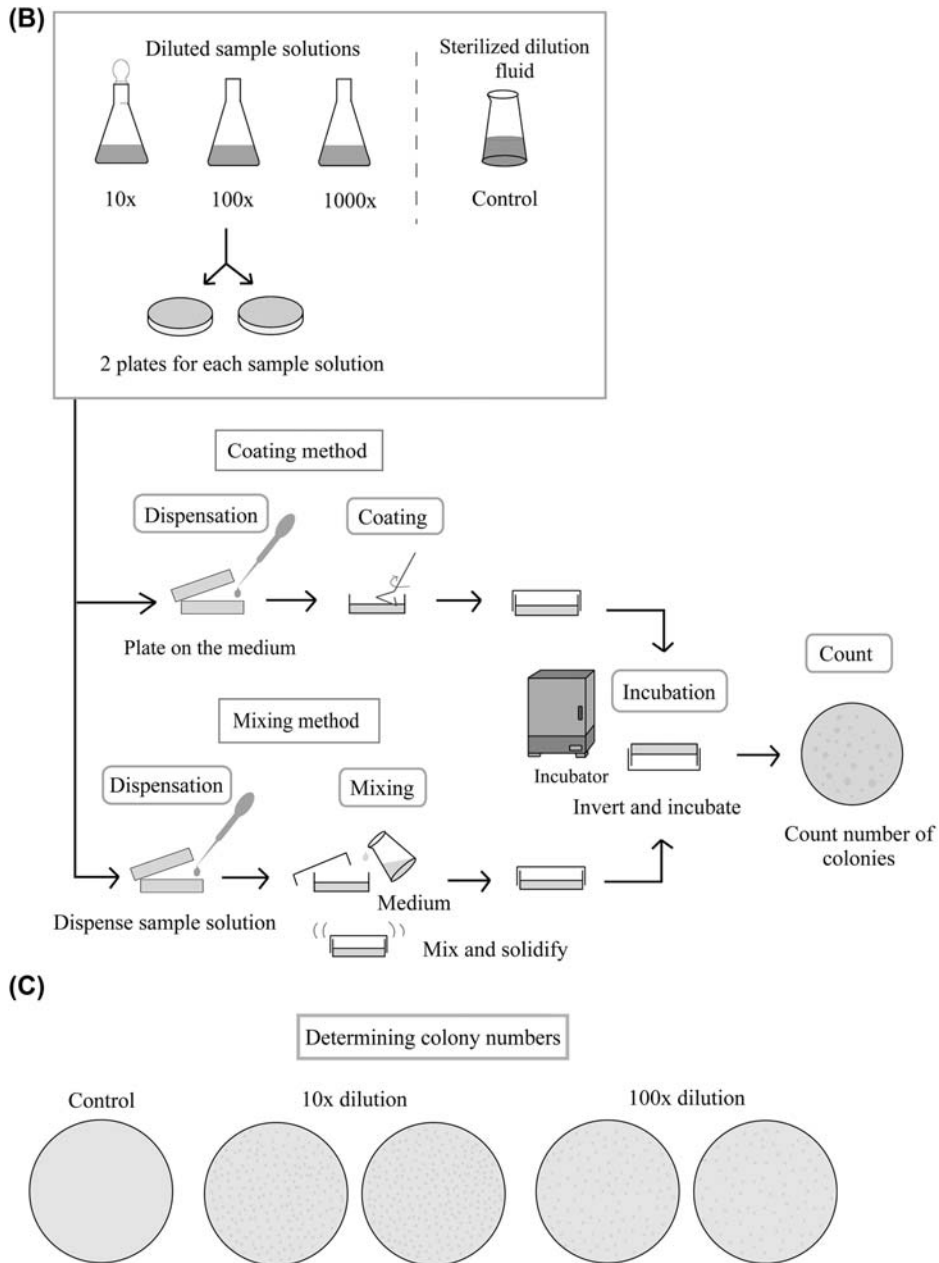


FIGURE 24.4 Cont'd

optimized conditions, times, and temperatures. Fig. 24.4C shows the method for calculating the number of microorganisms per sample.

24.3.6 Examples of reports of microbiological testing in PFALs

Much literature concerning the production of food exists, yet initiatives and research reports focusing on hygiene management in PFALs remain few in number (Uehara et al., 2011), as do similar studies in PFALs themselves (Hayakumo et al., 2013).

A study does exist concerning microbiological monitoring of airborne microorganisms and surface-attached microorganisms (Hayakumo et al., 2013). This study compares the number of bacteria and fungi in greenhouses and in PFALs. It reports a lower number of airborne microorganisms (bacteria at 0–4 CFU/m³, fungi at 16–24 CFU/m³), as well as surface-attached microorganisms (bacteria at 100 CFU/25 m², fungi at 1–51 CFU/25 m²) in PFALs.

There is a report on microbiological testing of vegetables, including products from PFALs, covering the past 12 years (Uehara et al., 2011). It reports the number of bacteria for each kind of vegetable and production procedure. The distribution of bacteria per unit (1 g) is 10²–10⁶ CFU in PFALs. The numbers for PFAL vegetables are values two to three orders lower when compared to those for other growing environments (outdoor cultivation: 10²–10¹⁰ CFU, hydroponic cultivation: 10³–10⁹ CFU) (Uehara et al., 2011). In such PFALs, the environmental control and hygiene management make the presence of fewer microorganisms possible. Other reports show bacteria at less than 300 (= 3.0 × 10²) CFU (Ooshima et al., 2013), 10²–10⁴ CFU (Sasaki, 1997), and 1.2 × 10⁶ CFU (Nagayama, 2012). Vegetables grown in PFALs are mostly leaf vegetables and tend to be eaten raw, which is the reason why environment control and hygiene management are important.

Some reports also exist concerning trials on culture solutions (Sasaki, 1997) and storage trials (Tokyo Metropolitan Institute of Public Health, 2011). One report analyzes changes in culture solutions over time and describes the importance of culture solution hygiene management (Sasaki, 1997). The results of vegetable storage trials (Tokyo Metropolitan Institute of Public Health, 2011) demonstrate temperature-based influence. More so than outdoor-cultivated vegetables, PFAL vegetables show sudden increases in their bacteria numbers as temperature rises. Moreover, PFAL vegetables obtained directly from the factory have bacteria at 10¹–10⁵ CFU (Tokyo Metropolitan Institute of Public Health, 2011). With regards to lettuce, there is a report that acknowledges significant differences in predistribution and postdistribution lettuce bacteria numbers (Sasaki, 1997). According to the results of a questionnaire about environment and production controls, no standardized temperature for delivery in the distribution process exists, with the information indicating a nonuniform state of affairs that varies with each PFAL, including cold storage only in summer, delivery at less than 5°C, and delivery at less than 10°C (Tokyo Metropolitan Institute of Public Health, 2011). In addition, a correlation between bacteria numbers and distribution temperatures was found. A report found that vegetable bacteria numbers only decreased by a factor of 1–2 log after washing (International Commission on Microbiological Specifications for Foods (ICMSF), 2011). Therefore, it is known that improved individual hygiene awareness and control of distribution processes and storage temperatures are important.

It is said that, when compared with other cultivation methods, bacteria numbers are lower in vegetables produced in PFALs. However, if appropriate temperature control does not occur in the distribution process, then the advantage vegetables produced in PFALs have of being produced in a

biologically clean airspace can be easily lost. For this reason, management of hygiene at all stages of the food chain, from production to distribution, is of greater importance in PFALs.

In recent years in Japan, a Third Party Accreditation Committee on Products and Product Systems (TPAC-PPS) in PFALs has been launched, and assessments have been carried out in the four fields of environment, safety/peace-of-mind, universality, and sociality (Inoue, 2012). The committee focuses on microbiological factors such as the numbers for live bacteria, *Coliform* groups, and *E. coli* O157 in PFALs. Microbiological standards have also been established, with three certification levels (Gold, Silver, Bronze) created.

In recent years, the safety of PFAL products and product systems has been emphasized. Consequently, there will most likely be increased need and progress with respect to research in the field in the future.

24.4 Concluding remarks

This chapter has focused on PFAL microbiological testing and described examples of testing methods and reports for the same. As also mentioned previously, no rules concerning microbiological testing exist. Kozai (2012) states that bacteria in PFALs usually number less than 300, which is less than 1/100th the number for greenhouse plants, and less than 1/500th the number for outdoor cultivation. Other than this report, it can be said that no other literature exists and that no particular attention has been paid with respect to microorganism numbers. Therefore, the current state is one in which each producer has their own management standardized protocols (Pak et al., 2014).

In recent years, interest has grown in microbiological testing. In Japan, discussions aimed at bringing Japan into accord internationally with testing methodologies such as the broadly internationally recognized ISO and Bacteriological Analytical Manual (BAM) methods are proceeding. With the recent emphasis on food safety, there is an increasing level of priority concerning microbiological testing. Rapid methods with confirmed validity will become indispensable, and further progress will surely be made in future research.

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Design and management of PFALs 25

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25.1 Introduction

In order to design and manage a plant factory with artificial lighting (PFAL) properly, it is necessary to understand various scientific, technical, and business fields related to PFALs. These fields include light sources and lighting systems (LSs), environmental measurement and control, management of energy, materials and workers, sanitation control, plant ecophysiology, hydroponics, plant nutrition, automation, cost/benefit analysis, finance, fresh food marketing, and sales promotion.

A variety of computer-assisted tools for design and management (D&M) of manufacturing factories are available in many industries. However, there are few such tools available for PFALs, which are an emerging technology and business. Accordingly, a computer-assisted D&M tool for PFALs needs to be developed based on methods and techniques common to computer-assisted tools used in other industries. It should be noted, however, that a PFAL is used to produce living organisms, i.e., plants, and so a core part of the PFAL D&M is the plant–environment–cultivation room interaction model.

In the first part of this chapter, the features, structure, functions, and usefulness of our PFAL-D&M system are introduced. In the second part, some typical outputs for the hourly and monthly electricity consumptions, coefficient of performance (COP) of air conditioners, light and temperature distributions, plant growth measurements, and analysis of the PFAL-D&M are presented.

25.2 Structure and function of the PFAL-D&M system

The PFAL-D&M system consists of three parts: design, management, and database (Fig. 25.1). The PFAL-D&M software is stored in the “cloud service” area for use via the Internet, except for the “data acquisition and upload (Data)” part of “production management (PM)” in the PFAL-M subsystem (Fig. 25.2).

There are two types of data acquisition and upload part (Fig. 25.3). Type A is designed to be installed at an existing PFAL, in which the data acquisition and upload part (sensors and data uploader)

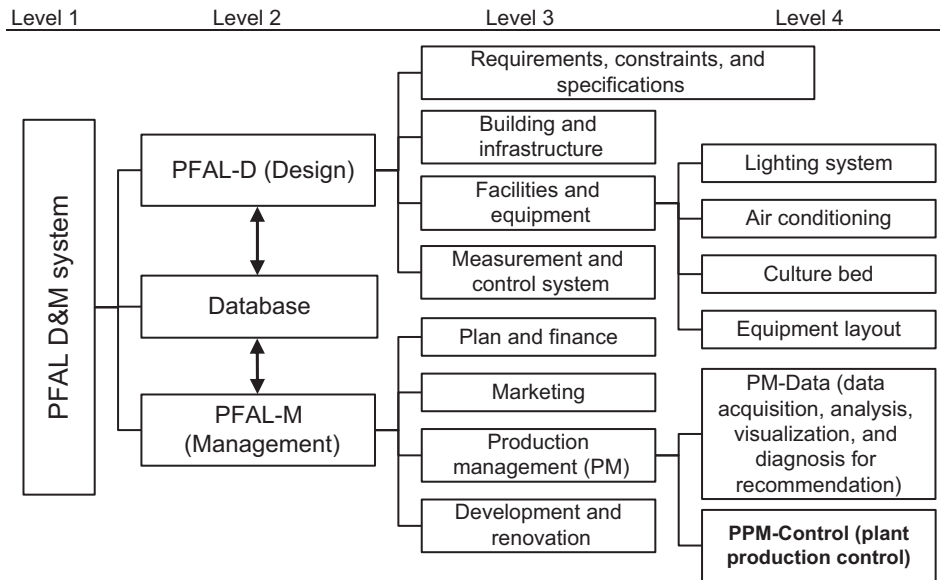


FIGURE 25.1

Structure of PFAL-D&M (plant factory with artificial lighting—design and management) system.

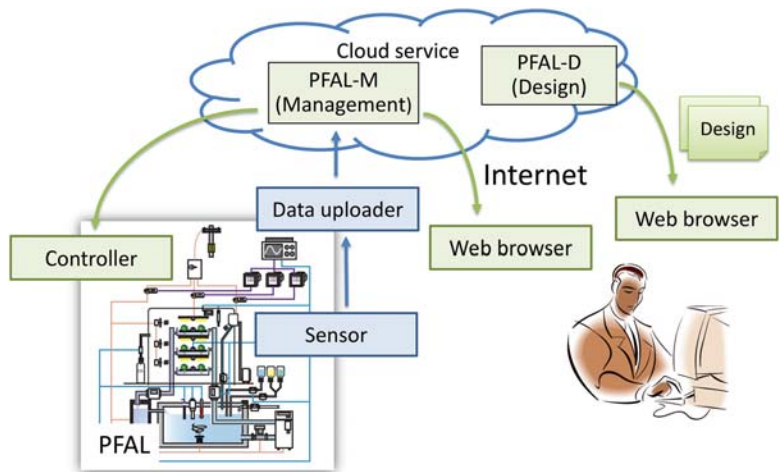


FIGURE 25.2

Structure of PFAL-D&M system, in the cloud and PFAL. Database common to PFAL-M and PFAL-D is also stored in the Cloud.

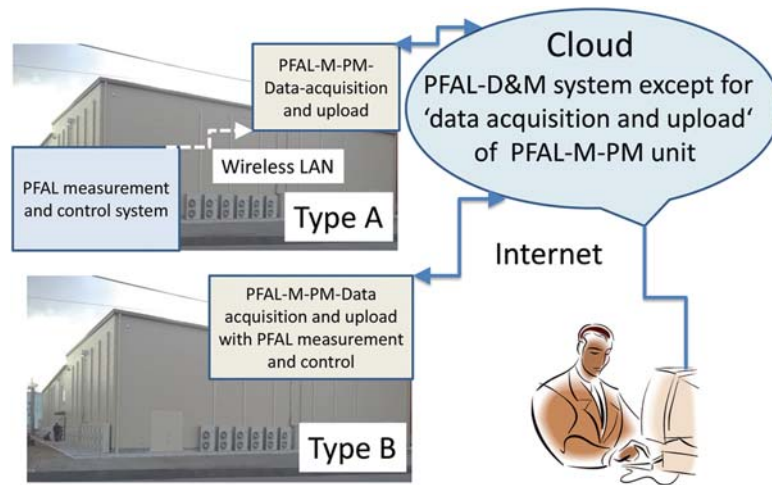


FIGURE 25.3

PFAL-D&M is used via Internet. Type A: installed at an existing PFAL; Type B: installed at a newly built PFAL.

of PFAL-M-PM-Data is basically separated from the measurement and control system of the existing PFAL. In Type A, there may be a small difference in measured temperatures between the two sensors, because the two temperature sensors may have different accuracies and may be installed at different places (e.g., one by the air conditioner and the other at the center of the culture room). In this case, PFAL-M-PM-Data cannot collect the temperature data used for its control. The same applies for other environmental factors. Type B is designed to be installed at a newly built PFAL, in which the data acquisition and upload part is embedded in the measurement and control system of the PFAL. Then, the air temperature used for its control is transmitted to the database of the PFAL-M-PM Data part and the air temperature used for its control can be stored.

25.3 PFAL-D (design) subsystem

The PFAL-D subsystem consists of the parts “requirements, constraints, and specifications,” “building, and infrastructure,” “facilities and equipment,” and “measurement and control” (Fig. 25.4). The whole PFAL-D subsystem is stored in the “cloud service” area.

25.3.1 Lighting system (LS)

The cost for electricity accounts for about 20% of the total production cost while the cost for LED lighting accounts for 70%–80% of the electricity cost. Since it is difficult to improve the hardware of the LS after constructing the PFAL, a good hardware design of the LS is essential.

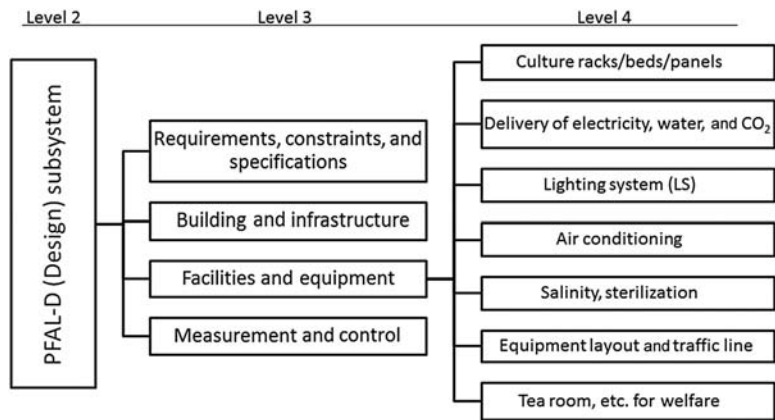


FIGURE 25.4

Structure of PFAL-D (design) system.

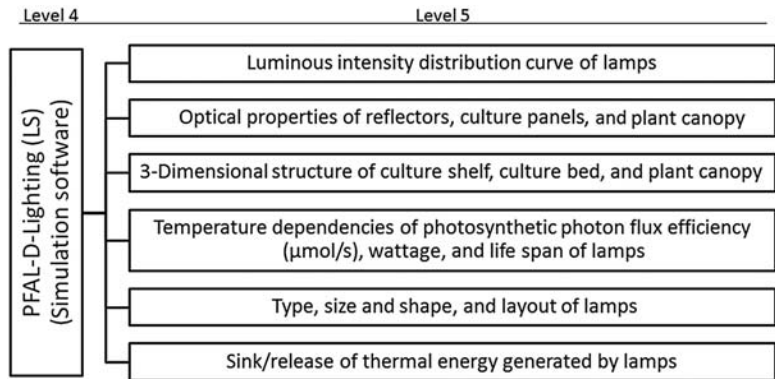


FIGURE 25.5

Parameters used to simulate the light environment (time courses of spectral and spatial distributions) using PFAL-D-LS (design of lighting system). Cultivation is used as synonym for culture in this chapter.

The software of the “LS” part is customized for the PFAL to simulate the light environment as affected by the parameters shown in Fig. 25.5. The simulated light environment using mathematical equations based on optical physics is, in general, fairly accurate and useful.

When designing the LS, it should be noted that the spatial and spectral distributions of photosynthetic photon flux density (PPFD) above the culture or cultivation shelf are affected by the three-dimensional structure of the culture or cultivation shelf and the optical properties of the plant community. (The term cultivation is used as a synonym for culture in this chapter.) Also, the design of the heat energy source/sink of lamps such as LEDs affects the temperatures of the LEDs, and thus the photosynthetic photon efficiency of the lamps.

25.4 PFAL-M subsystem

25.4.1 Structure of software

The PFAL-M subsystem consists of the “plan and finance,” “marketing,” “PM,” and “development and renovation” parts. “Plan and finance” are executed in line with the vision, mission, and goals of the PFAL. Marketing includes customer development, product development, sales promotion, and product and service delivery.

The PFAL-M-PM part is divided into PM-Data and PM-Control. PM-Data is further divided into three parts: (1) data acquisition and upload, (2) data processing, analysis, and visualization, and (3) diagnosis and recommendation for improvements. Data collected by the PFAL-M-PM-Data part are processed, analyzed, and visualized for each factor and/or combinations of the factors as shown, for example, in Fig. 25.6. The data collected by PFAL-M-Data are used to calculate various indices such as resource use efficiencies (RUE) to express the cost performance or monetary productivity of the plant production system in the PFAL (Fig. 25.7). The PFAL-M-PM-C (control) part consists of: (1) production costs, sales, and revenues; (2) seeding, seedling production, and cultivation; (3) harvesting, packing, cooling, and shipping; and (4) order receipt, order, and stock management.

25.4.2 Logical structure of equations

All the variables, equations, and constants/coefficients used in PFAL-D&M are systematically tabulated as shown in Fig. 25.8. Fig. 25.9 shows a part of the structured map in PFAL-D&M, which includes 72 measured data, 73 indices, five set points, 22 constants/coefficients, and many equations.

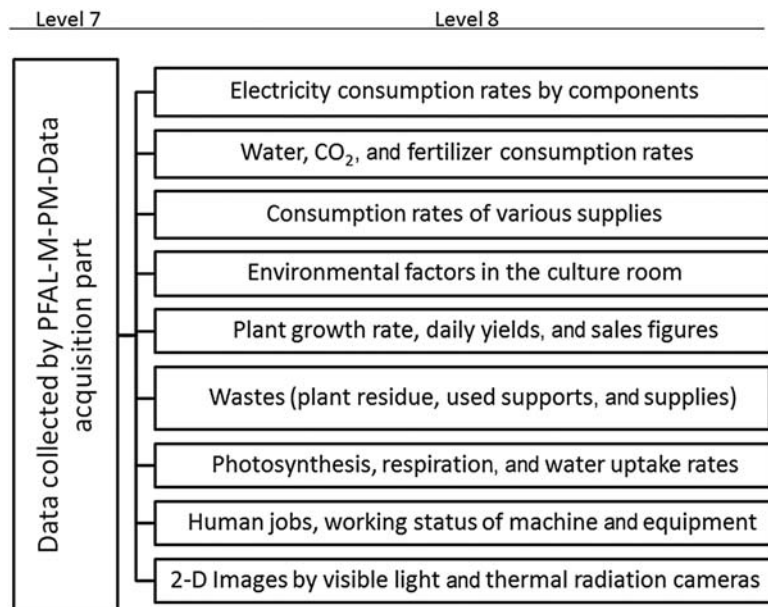


FIGURE 25.6

Data collected by PFAL-M-PM Data acquisition part.

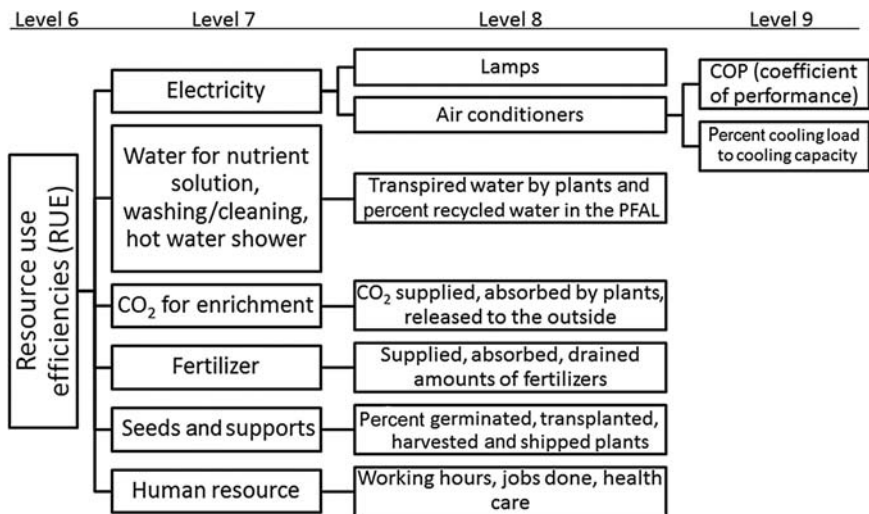


FIGURE 25.7 Resource use efficiencies (RUE) to be displayed on the screen. RUE is the ratio of the amount of each resource fixed in the salable part of produce to the resource input.

① Serial number ② Variable name ③ Symbol ④ Unit ⑤ Category ⑥ Time interval ⑦ Equations ⑧ Equations in TEX ⑨ URL ⑩ Definition ⑪ Explanations ⑫ Reference ⑬ Equation number ⑭ Variable name in English

①	②	③	④	⑤	⑥	⑦	⑧	⑨	⑩	⑪	⑫	⑬	⑭
1	Electricity	E	kWh	Energy	1 day								
2	Water for nutrient solution, washing/cleaning, hot water shower	W	m ³	Water	1 day								
3	CO ₂ for enrichment	CO_2	kg	CO ₂	1 day								
4	Fertilizer	F	kg	Fertilizer	1 day								
5	Seeds and supports	S	kg	Seeds and supports	1 day								
6	Human resource	H	h	Human resource	1 day								
7	Lamps	L	W	Light	1 day								
8	Air conditioners	A	W	Light	1 day								
9	Transpired water by plants and percent recycled water in the PFAL	T	m ³	Water	1 day								
10	CO ₂ supplied, absorbed by plants, released to the outside	CO_2	kg	CO ₂	1 day								
11	Supplied, absorbed, drained amounts of fertilizers	F	kg	Fertilizer	1 day								
12	Percent germinated, transplanted, harvested and shipped plants	P	%	Plant	1 day								
13	Working hours, jobs done, health care	H	h	Human resource	1 day								
14	COP (coefficient of performance)	COP		Light	1 day								
15	Percent cooling load to cooling capacity	PCL	%	Light	1 day								

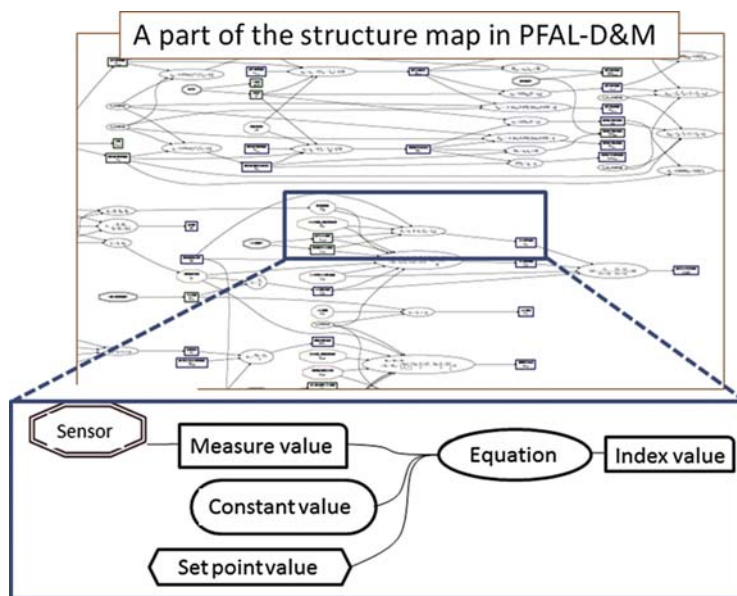
250 equations in this table

Variables

Electricity consumption

Light

FIGURE 25.8 Tabulated list of variables used for electricity consumption and light environment together with their attributes (1) to (14) stored in PFAL-M. The variables used for CO₂, water, heat energy, plant growth, etc. are also stored in the same way.

**FIGURE 25.9**

A part of the structure map in PFAL-D&M showing how to obtain the index value from the measured value, constant value, set point value, and equation.

The most important equations with explanations are given in Chapter 5 of this book and Kozai (2013). This software can be used to optimize the environmental conditions and thus maximize the cost performance of the PFAL, for example (Fig. 25.10).

25.5 Design of the lighting system

25.5.1 PPFD distribution

The PPFD distribution on the culture panel can be well simulated by PFAL-D&M (LS). Fig. 25.11 shows a simple simulated result of the two-dimensional PPFD distribution on the cultivation panel with and without a light reflector set above the light sources. The results show that the average PPFD is increased by 38% using a white reflector, compared with the one without a reflector.

Fig. 25.12 shows a simple simulated result of the three-dimensional PPFD distribution over model crisp lettuce heads planted in a grid-like fashion on the cultivation panel. Using this software, the ratio of light energy received by plants to that the light emitted by the light source can be estimated. Thus, the software tool is useful for designing the planting density, vertical distribution of PPFD, etc. More and detailed examples are provided in Kozai et al. (2016).

25.5.2 Scheduling the lighting cycles to minimize the electricity charge

The lighting time schedule considerably affects the “ad valorem” electricity charge, which is basically proportional to the integral of electricity consumption (kWh). However, the hourly ad valorem charge depends on the time zone and season in countries such as Japan.

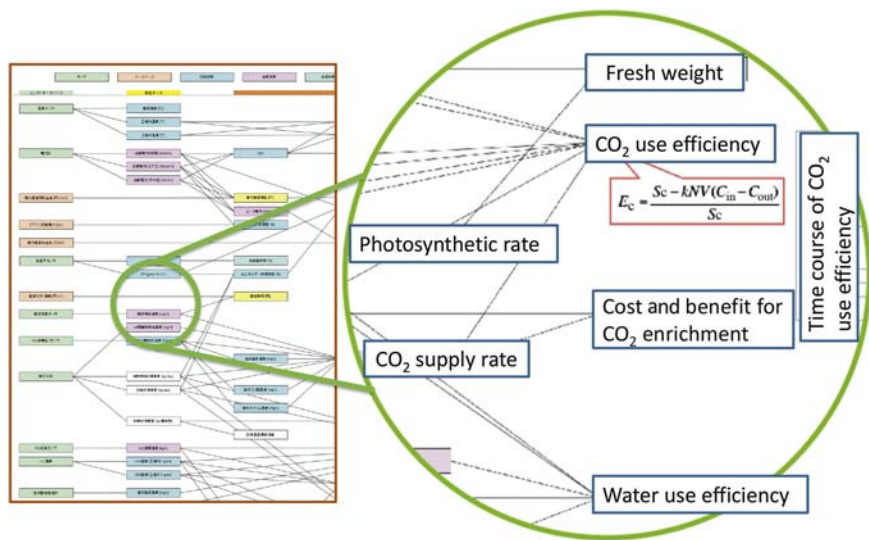


FIGURE 25.10

A logical structure of the equations stored in PFAL D&M. The equations listed in Fig. 25.8 are logically connected as shown here (left). The variables in the circle (right) show the indices such as CO₂ and water use efficiencies and rates of photosynthesis and CO₂ supply (see also Fig. 25.7).

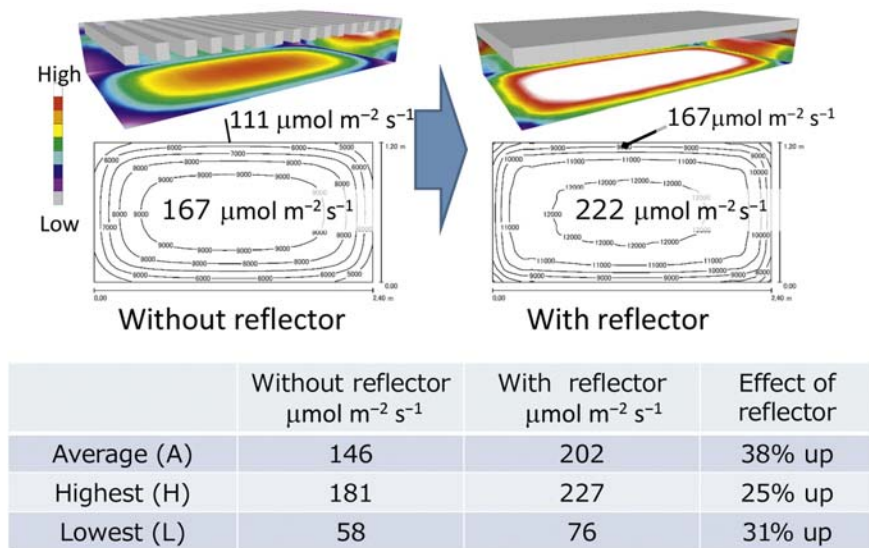
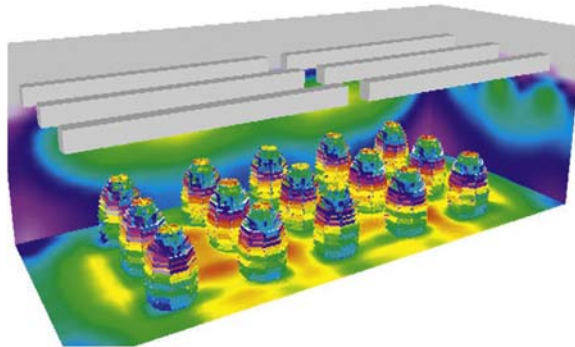


FIGURE 25.11

An output example of PFAL-D for light environment improvement by use of a light reflector.

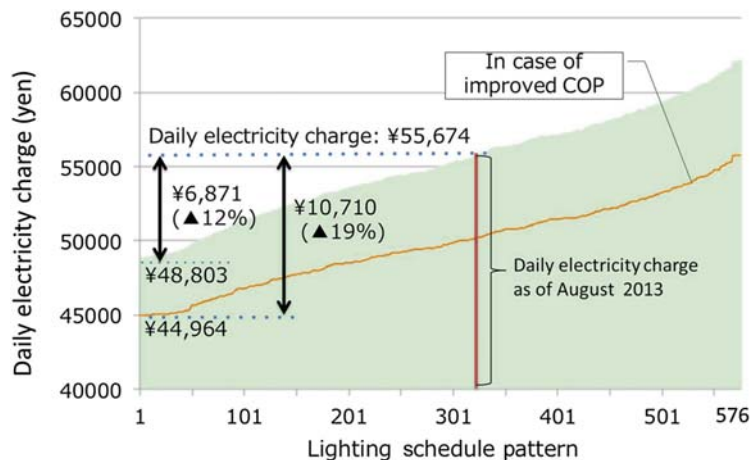
**FIGURE 25.12**

A simple simulated result using PFAL-D of the three-dimensional PPFD distribution on crisp lettuce heads planted.

If the lamps are divided into two groups and each lamp group is turned on for 16 continuous hours starting on the hour, every hour (0:00, 1:00, 2:00, and so on), there will be 576 (24×24) combinations of lighting time schedule. Fig. 25.13 shows the daily ad valorem electricity charges of 576 combinations assuming the charge system for the summer of Tokyo Electric Power Co., Inc.

The daily electricity charge of an existing PFAL was 55,674 yen in August 2013. However, based on simulation results, it can be reduced to 48,803 yen by simply changing the lighting time schedule (the daily integral of electricity consumption remains unchanged).

The daily electricity charge shown in Fig. 25.13 is affected also by the COP of air conditioners as discussed in the next section. If the number of air conditioners in operation is changed to keep the COP high, the daily electricity charge is reduced to 44,964 yen.

**FIGURE 25.13**

Daily “ad valorem” electricity charge as affected by lighting time schedule in Tokyo (1 US\$ = 120 yen) on the software.

In the case of three lamp groups, there are 13,824 ($= 24 \times 24 \times 24$) combinations of lighting time schedule. By using the PFAL-D (lighting), the lighting time schedule providing the lowest electricity charge for lighting and air conditioning can be found among a large number of candidates.

25.6 Electricity consumption and its reduction

The PFAL-M-PM-Data part handles the data acquisition, processing, and visualization regarding the rate and state variables in a PFAL, including the electricity consumption.

25.6.1 Daily changes in electricity consumption

The hourly ad valorem electricity charge depends on the time zone and season in Japan. It is highest in summer during 13:00–16:00 and is lowest during 22:00–8:00 the next morning (nearly 50% discount at nighttime). Thus, electricity cost can be significantly reduced by setting the light period to 22:00–8:00 (10 h) and to the other 6 h before 22:00 and/or after 8:00, thus avoiding the period of 13:00–16:00. The monthly sum of daily electricity consumption is mostly determined by the lighting time schedule, COP (for the definition, see the next section) of air conditioners, and the time zone-dependent electricity charge system.

Fig. 25.14 shows an example of hourly changes in electricity consumption of the culture room with nine tiers in August for lamp groups A (five tiers) and B (four tiers) and air conditioners of a PFAL in Japan. All the lamps are turned on for 16 continuous hours a day but the starting time of the light period for each tier out of the nine tiers is different. The hourly change in averaged COP of the seven air conditioners is given by the line in Fig. 25.14, which is higher when the outside air temperature is lower.

25.6.2 COP as affected by the temperature difference between inside and outside

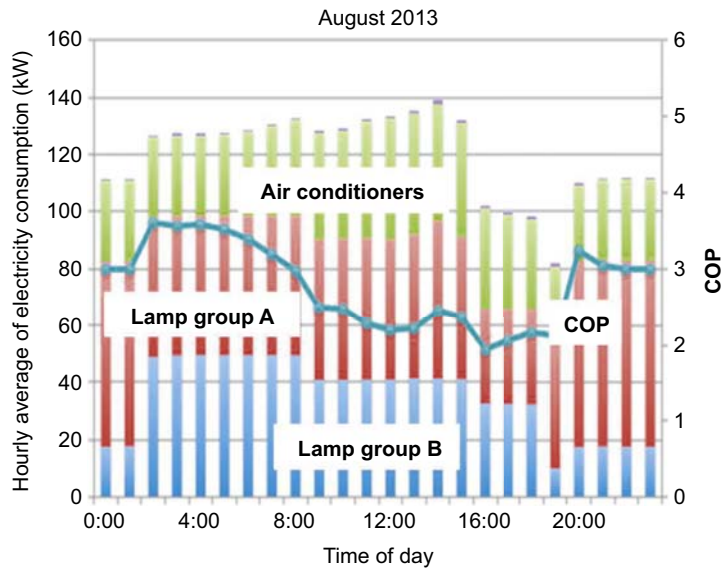
The COP (the ratio of the cooling load of the culture room to the electricity consumption of the air conditioners), or electrical energy use efficiency of air conditioners, is influenced by several factors.

Fig. 25.15 shows the COPs in summer as affected by the difference in air temperature between inside and outside the culture room. Since the room temperature is always 22°C, the COP decreases with increasing outside temperature. The COP increases to around 10 in winter, because air temperature is 5–25°C higher inside than outside (not shown in Fig. 25.15).

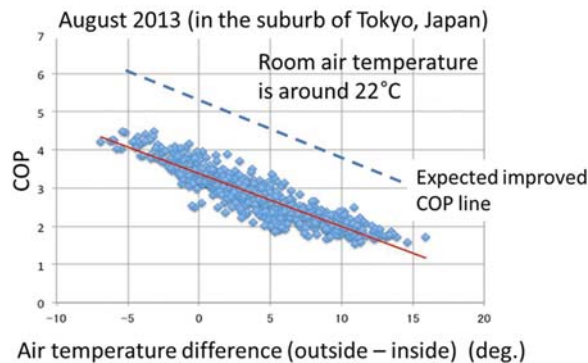
The lower the COP, the higher the electricity consumption of air conditioners, and thus the electricity cost, especially during 13:00–16:00. It is important to set the light period at nighttime (when air temperature outside is lower than daytime) to achieve a higher COP, even if a nighttime discount of electricity charge is not available.

25.6.3 COP as affected by the actual cooling load

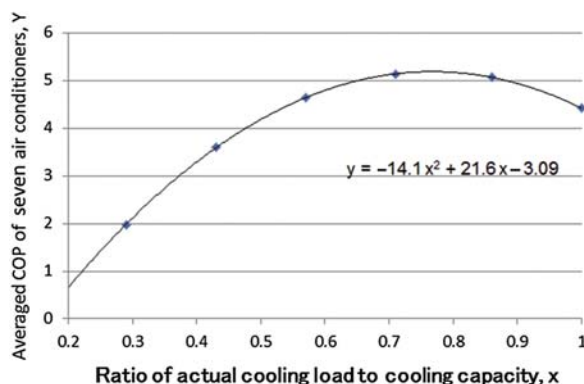
The COP is also affected by the ratio of actual cooling load to the cooling capacity of the air conditioners (Fig. 25.16). The COP increases with increasing ratio up to 0.7–0.8 but decreases when it is over 0.8 (Sekiyama and Kozai, 2015). The actual cooling load was estimated as the total electricity

**FIGURE 25.14**

An example of daily changes in electricity consumption by lamp groups A and B, and COP (coefficient of performance or electrical energy use efficiency) of air conditioners in a PFAL. Lamps of each tier are turned on together for 16 continuous hours a day, but the light period is shifted. COP of air conditioners is higher at lower outside air temperature.

**FIGURE 25.15**

COPs of air conditioners in August as affected by air temperature difference between inside and outside. Electricity cost for air conditioning is halved when COP is doubled. The dashed line indicates the maximum possible COP which is achieved when the cooling load is around 70% of the cooling capacity (see also Fig. 25.16).

**FIGURE 25.16**

Averaged COP of seven air conditioners as affected by the ratio of actual cooling load to full cooling capacity. Total electricity consumption of seven air conditioners at full cooling capacity is 58.6 kW (Sekiyama and Kozai, 2015).

consumed by the lamps, air circulation fans, and nutrient solution pumps. The variations of COP for the same temperature difference in Fig. 25.15 are caused mainly by the ratio of actual cooling load to the cooling capacity, indicating that the number of air conditioners in operation needs to be adjusted to keep the ratio in the range of 0.7–0.8.

Fig. 25.17 shows the diurnal time course of power consumption of each of 10 or four air conditioners. From 1:00 to 17:00, 10 air conditioners were turned on, but four air conditioners only were turned on after 17:00. In either case, air temperature was controlled at the set point of 22°C. Average COP of air conditioners in operation was 20%–25% higher after 17:00 than before 17:00. Thus, it is important to control the number of air conditioners in operation depending on the actual cooling load in order to achieve a high COP and thus reduce the electricity consumption.

25.6.4 Monthly changes in electricity consumption

Fig. 25.18 shows the monthly electricity charge for a PFAL producing about 100,000 leaf lettuce heads per month. The percent basic charge is lowest (12%) in summer and highest in winter (16%) with an average of 16%. In Japan, the monthly basic charge is determined by the maximum 30-min power consumption (kW) during the past year. In Fig. 25.18, the basic charge can be reduced by reducing the maximum 30-min power consumption during 3 months in summer. Reducing the annual maximum consumption by smoothing it over time is essential to reduce the yearly total of the monthly basic charge.

25.6.5 Visualization of power consumption by components on the display screen

Fig. 25.19 shows an example of visualized power consumption by components on the computer display screen as a daily report automatically generated by the PFAL-M&D-M. This kind of report can be

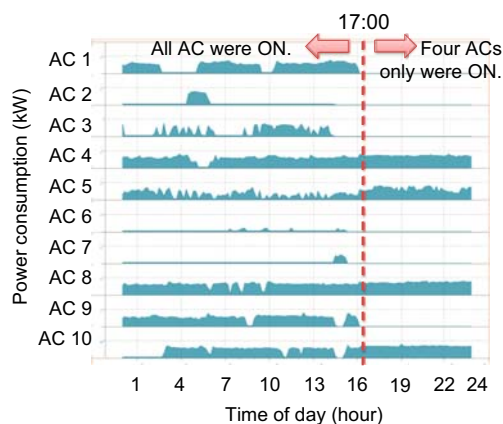


FIGURE 25.17

Diurnal courses of power consumptions of air conditioners (AC). From 1:00 to 17:00, all (10) ACs were turned on, but four ACs only were turned on after 17:00. In either case, air temperature was controlled at the set point of 22°C. Average COP of ACs in operation was 20%–25% higher after 17:00 than before 17:00, showing the importance of the control of ACs in operation.

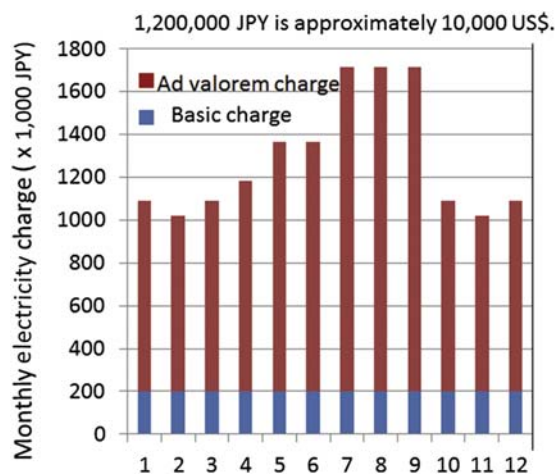


FIGURE 25.18

An example of monthly electricity charge for a PFAL in Japan, producing about 100,000 leaf lettuce heads per month. Percent basic charge is lowest (12%) in summer and highest in winter (16%) with an average of 16%. In Japan, the monthly basic charge is determined by the maximum 30-min power consumption (kW) during the past 1 year.

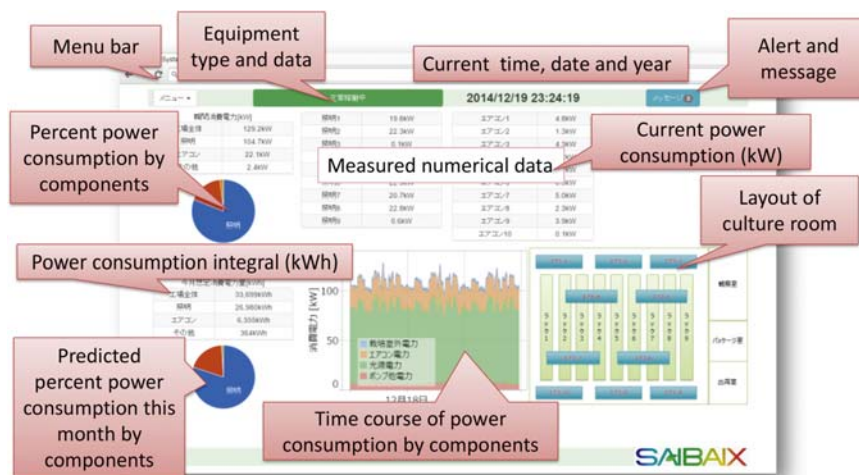


FIGURE 25.19

Visualized daily report of power consumption by components on the computer display screen for the PFAL manager as a daily report.

generated weekly, monthly, and yearly, or upon request by the PFAL manager. With this report, the PFAL manager can grasp the status and progress of the PFAL, and easily identify problems that need to be solved or improved. A radar chart is also useful to understand the overall performance of the PFAL at a glance. Fig. 25.20 is a typical radar chart showing the overall performance of electricity cost management.

25.6.6 Rates of net photosynthesis, dark respiration, and water uptake by plants

Based on the CO_2 , water, and energy balance equations for the culture room, the hourly and daily changes in net photosynthetic rate, dark respiration rate, and water uptake rate of plants in the culture room can be estimated and visualized. These data can be related to the total projected leaf area and can be used to determine the parameter values for mathematical models of plant photosynthesis, dark respiration, and transpiration (for details of equations, see Chapter 5).

25.7 Three-dimensional distribution of air temperature

Plant growth is directly affected by temperature. Thus, achieving uniform spatial air and plant temperature distributions in the entire culture room is essential to ensure uniform plant growth. PFAL-M-PM-Data collects temperature data in the culture room at 100–200 different measuring points, and presents the three-dimensional distribution of temperature in the culture room.

Figs. 25.21 and 25.22 show the layout of culture tiers together with the three-dimensional air temperature distributions (can be hourly, daily, and weekly averages). These uneven distributions of air temperature are mainly caused by the uneven air flows from the air circulation fans of air conditioners,

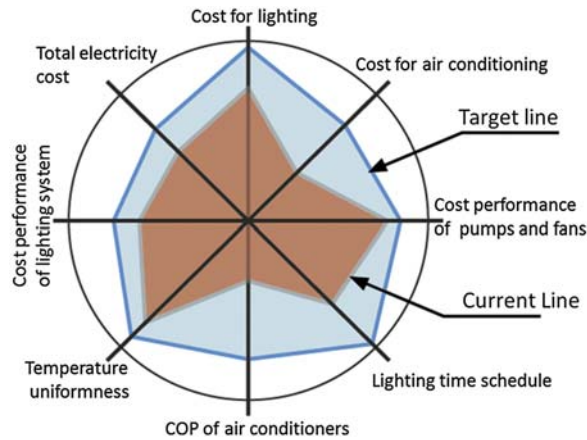


FIGURE 25.20

Radar chart showing the overall performance of electricity charge management to clarify the points to be improved. Each axis is automatically scaled.

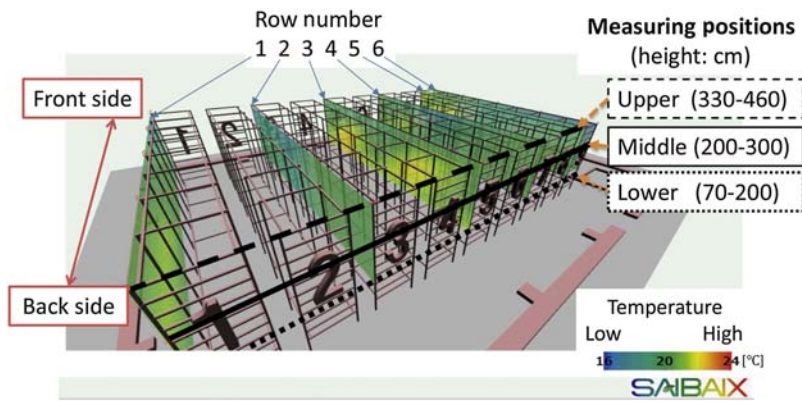
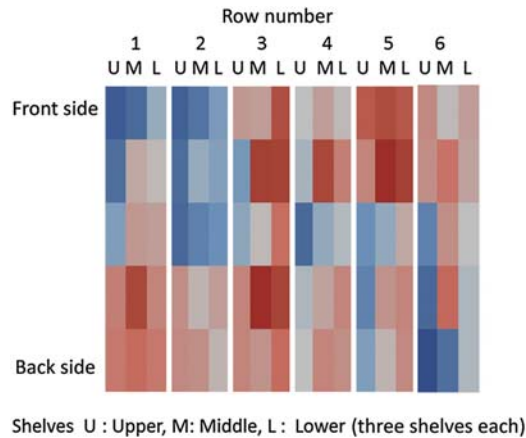


FIGURE 25.21

An example of three-dimensional air temperature distribution in the culture room with nine rows and 10 tiers in the PFAL.

natural convection due to heat energy generated from lamps, and air flow resistance due to culture shelves with reflectors. Once the three-dimensional uneven distributions of air temperature are visualized, it is relatively easy to improve the distributions by changing the direction and number of air circulation fans in operation. A thermal imaging camera for measuring the surface temperatures of walls, floor, culture shelves, and plants is also useful to find the points that may cause uneven temperature distribution and water condensation.

**FIGURE 25.22**

Three-dimensional air temperature distributions in the culture room of PFAL. U, M, and L denote the upper, middle, and lower shelves. For row numbers, floor layout, and heights of shelves, see Fig. 25.21.

25.8 Plant growth measurement, analysis, and control

25.8.1 Determination of parameter values for the plant growth curve

Plant growth (fresh/dry weight, leaf area, volume, etc.) in a plant community is well expressed by a logistic growth curve as shown in Fig. 25.23. Based on the measurement of plant growth, PFAL-M-PM finds the parameter values of the plant growth curve. In the equation in Fig. 25.23, the parameter values t , k , r , and $S_{\max}$ denote, respectively, time, initial value at t , relative growth rate, and maximum (saturated) value (“ e ” denotes the exponential function). The photographs on the right of the graph were taken from the top to estimate the projected leaf area of plants on the culture panel. The value r in the equation can be estimated from the photographs. The parameter values r and $S_{\max}$ are determined by planting density, environmental factors, genetic characteristics of plants, etc. Plant trait (canopy structure, physiological response, etc.) measurement or phenotyping is discussed in Kozai (2018).

25.8.2 Determination of dates for transplanting

Fig. 25.24 shows the effects of the first and second transplanting dates on the growth of projected leaf area. The growth is delayed and saturated after the percent projected area reaches 100%. If the first and/or second transplanting is conducted after these dates, the productivity decreases. In addition, the work hours for transplanting increase because of overlapping with surrounding plants.

On the other hand, if the transplanting is conducted when the percent projected area is significantly lower than 100%, the efficiency of using the culture space and thus productivity decrease. PFAL-M-PM helps the production manager to decide the transplanting dates to optimize the productivity.

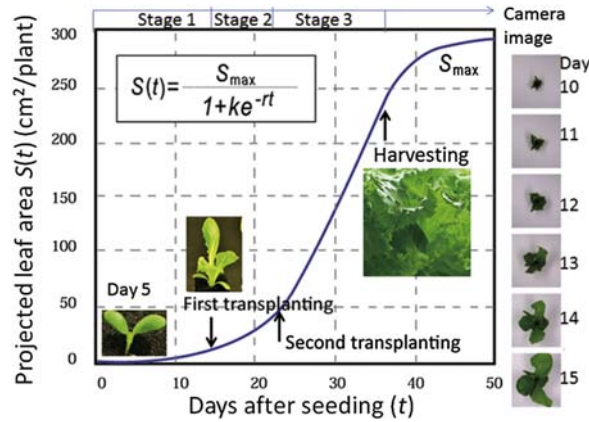


FIGURE 25.23

Plant growth curve expressed as logistic growth equation. Photos on the right were taken from the top. Stage 1: from seeding to first transplanting, Stage 2: from first transplanting to second transplanting, and Stage 3: from second transplanting to harvesting.

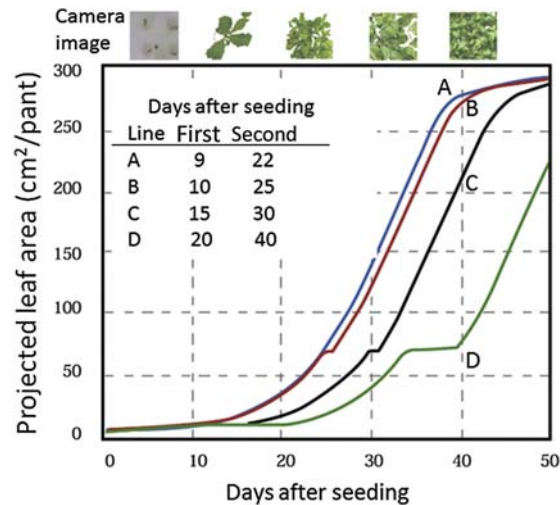


FIGURE 25.24

Projected leaf areas as affected by the days after seeding of first and second transplanting.

Table 25.1 Ratio of area occupied by the culture panels ($30 \times 60 \text{ cm}^2$ each) for plant growth Stages 1–3 as affected by days required and the number of cells (holes) per tray for the growth Stages 1, 2, and 3.

Growth stage	1	2	3	Total
Days required	D1 = 14	D2 = 10	D3 = 10	D1 + D2 + D3 = 34
No. of cells/tray	C1 = 300	C2 = 25	C3 = 6	—
Relative total number of panels required	$P1 \times D1 = 1 \times 14 = 14$	$D2 \times P1 \times C1/C2 = 10 \times 12 = 120$	$D3 \times P1 \times C1/C3 = 10 \times 50 = 500$	$PT = P1 \times (D1 + D2 \times C1/C2 + D3 \times C1/C3) = 634$
Relative area ratio of panels occupied	$P1 \times D1/PT = 0.0221$	$D2 \times P1 \times (C1/C2)/PT1 = 0.1893$	$D3 \times P1 \times (C1/C3)/PT = 0.7886$	$PT/PT = 1.0000$
No. of panels stored on the culture beds	$A/(P1 \times D1/PT) = 0.0221 \times 63,400 = 1401$	$A/(P1 \times (C1/C2))/PT = 0.1893 \times 63,400 = 12,001$	$A/(P1 \times (C1/C3))/PT = 0.7886 \times 63,400 = 49,984$	A = 63,386
No. of daily harvestable plants	—	—	49,984/10 = 4998	

The total number of panels stored on the culture beds in culture room A is assumed to be 63,400 and the success rate at each plant growth stage to be 1.0. The daily number of harvestable plants changes by changing D1–D3 and C1–C3.

25.8.3 Determination of the number of culture panels for different growth stages

Cultivation panels with different numbers of cells (holes) are used for growing plants with growth stages of 1, 2, and 3 (Chapter 21 and Fig. 25.24). Table 25.1 shows an example of the relative area occupied in the cultivation panels for growth stages 1–3 as affected by days required for the growth stages 1, 2, and 3 (D1, D2, and D3), and the number of cells per tray (C1, C2, and C3). D1–D3 and C1–C3 basically determine the plants produced per day. Once D1, D2, and D3 are fixed based on the growth analysis, the number of panels required for each day can be calculated using the equations given in Table 25.1. Success rates of a_1 , a_2 , and a_3 ($0 < a_1, a_2, a_3 < 10$) for each stage can be implemented in the equations. The production process in the PFAL can be reasonably managed based on this kind of theoretical consideration and computer software.

25.9 Conclusions

PFAL-D&M is expected to be useful for designing the culture room and managing the plant production process of PFALs. In the near future, PFAL-D&M will be able to cover about 70% of the software used to manage the plant production process. However, much remains to be done. It should be noted that some parts of the plant production system cannot be covered by PFAL-D&M, such as the microbial ecosystem and algae growth and propagation in the culture beds. It is therefore necessary to design and develop an entirely new PFAL cultivation system that makes plant PM much easier than existing systems.

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Automated technology in plant factories with artificial lighting

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26.1 Introduction

Pest and weed control, which are essential in open-field agriculture, are not necessary for vegetable production in plant factories with artificial lighting (PFAL), which are completely isolated from the outside environment. Depending on the PFAL's facilities, there is typically no work until harvesting after the plants are relocated. Therefore, the work to be automated includes seeding, transplanting, moving cultivation panels, harvesting, weight checking, packaging, metal inspection, and panel cleaning. Although it is debatable whether PFALs should be completely automated, [Ogura \(2011\)](#) has stated that humans should be involved at strategic points in the process.

In addition, the consumables and facilities of PFALs have not yet been standardized, and the size of cultivation panels and plant density per panel differ between facilities. General equipment for automation has also become made-to-order, and the cost of introduction is high. Hence, automated equipment has not been introduced in many PFALs.

Only a single cultivation layer was available for this study because PFALs at an early stage employ high-intensity discharge lamps. Under this condition, a spacing device to reduce the plant density as the plants grow was used to improve production efficiency. However, heat from the tube surface is reduced by the light source, so this light source should be replaced by a light-emitting diode (LED) or fluorescent light (FL) from the discharge lamp. A multistage process is then possible, dramatically increasing production efficiency. Therefore, improving production efficiency by using a spacing device is no longer very meaningful.

This chapter examines the automated devices used in the case study “Green Clocks Corporation (Osaka, Japan),” which was completed in September 2014.

The facility discussed here is a leading large-scale PFAL in Japan with a cultivation capacity of 5200 lettuce heads per day. It also received financial support from the Ministry of Economy, Trade, and Industry. The following three systems were used to reduce the operating cost by 40%: (1) a seedling sorting robot system (yield improvement); (2) an automated cultivation system (labor saving); and (3) LED light sources (energy saving). In particular, (1) and (2) are unique systems that were newly developed for this facility.

In this PFAL, the basic cultivation schedule is: seeding and greening, 4 days; nursery, 14 days; and cultivation, 18 days. Hence, it takes 36 days from sowing to harvesting. A transplant operation is performed twice during the production process; the first transplant is performed by a robot from the

greening process to the nursery panel, and the second is manually carried out from the nursery panel to the cultivation panel. Harvesting is done manually, and the heads of lettuce are shipped after packing and metal inspection. The automated devices and equipment used in this PFAL will be discussed in the following section.

26.2 Seeding device

The entire seeding device is shown in Fig. 26.1A. The suction holes, which have the same pitch as the sowing urethane mat (300 holes with dimensions of $300 \times 600 \text{ mm}^2$), are open to the suction plate at the top (Fig. 26.1B), through which the air is sucked. The coated seeds are thrown into the suction plate

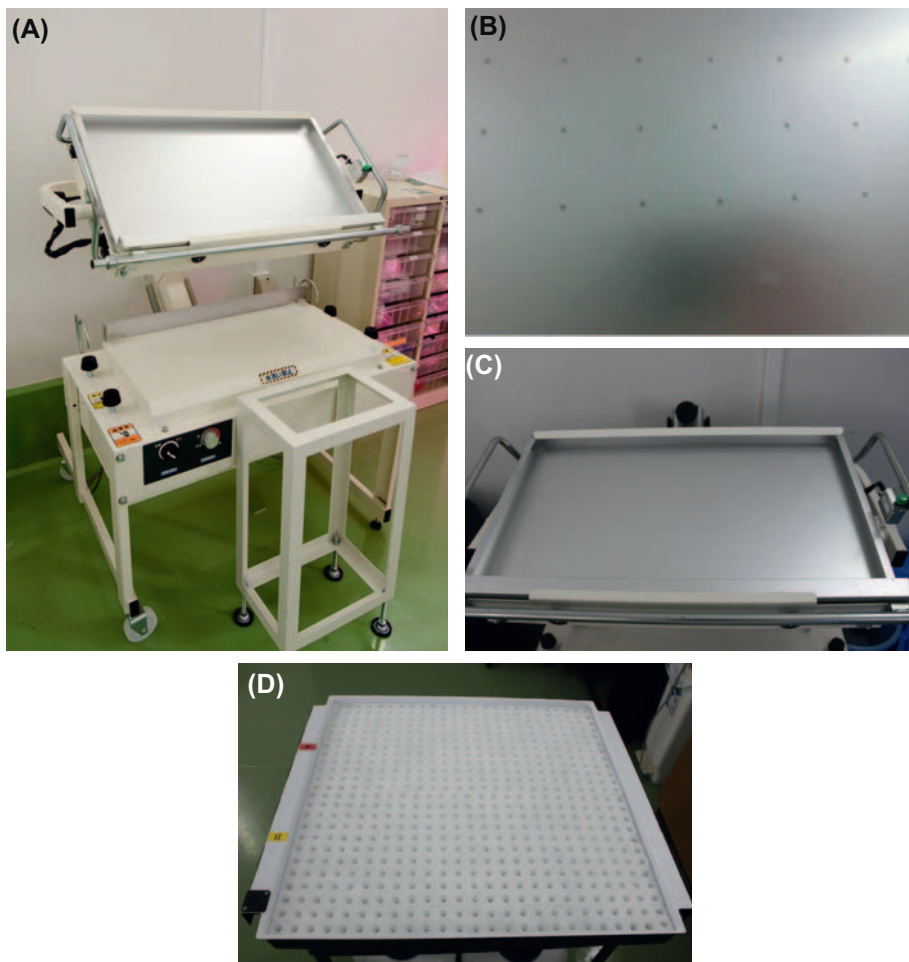


FIGURE 26.1

Seeding device: (A) appearance, (B) suction holes, (C) suction plate, and (D) sowing urethane mat.

(Fig. 26.1C), and the plate is manually moved back and forth to the left and right. Finally, the coated seeds fall into all the suction holes. At the same time, the sowing urethane mat with hemispherical holes of the same pitch as the suction plate is set on the lower table (Fig. 26.1D).

Next, the suction plate is manually turned upside down and brought into close contact with the sowing urethane mat. When the air suction is stopped, the coated seeds are released from the suction plate and fall into the sowing urethane mat, thus completing the seeding. If more than one seed is sucked into a suction hole, the device is able to remove the excess seeds by vibrating the suction plate.

An operator determines whether each suction hole contains a coated seed, then inverts the suction plate and shuts off the suction.

26.3 Seedling selection robot system

Five thousand excellent seedlings are selected from 6000 seedlings per day. Seedling selection is performed in the final stage of the seeding and greening process over 4 days in a greening room. Mechanization is essential for processing 6000 seedlings daily in terms of reliability and continuity. In addition, this facility uses the circadian rhythm in seedling diagnosis—the first such attempt worldwide to the best of the authors' knowledge. This technology aims to improve the accuracy of the diagnosis.

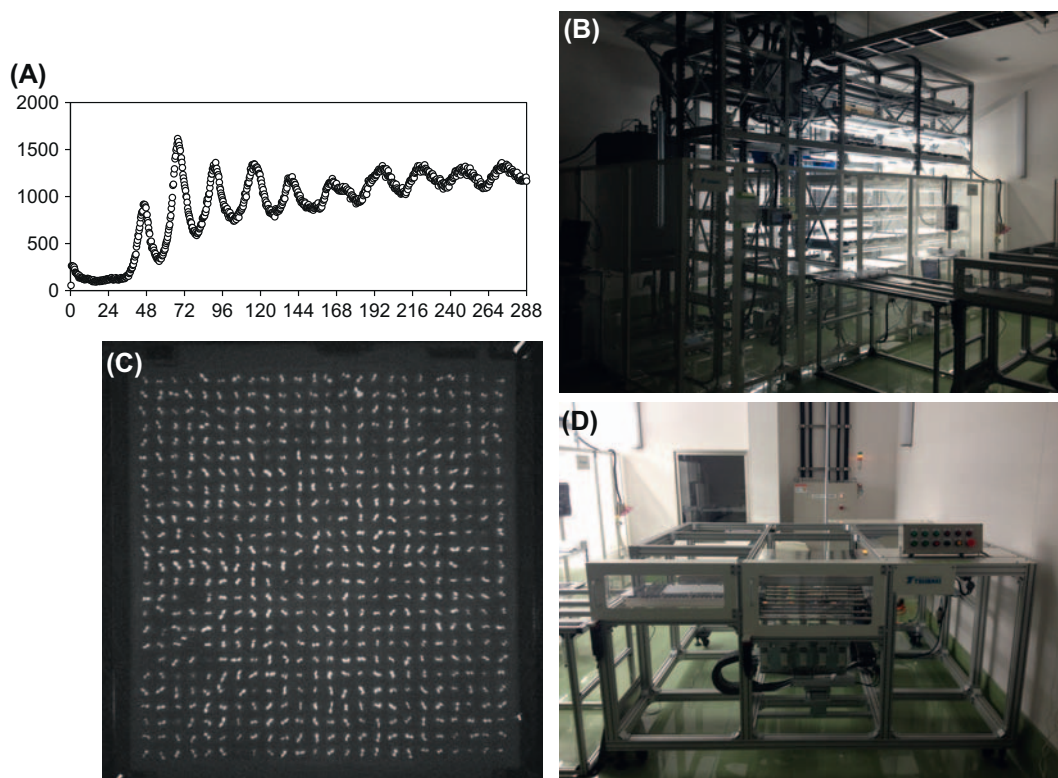
A versatile, high-speed image-processing system is generally adopted for large-scale seedling diagnosis. Usually, an image is only captured once to analyze the shape and size of the seedling. However, by measuring the seedlings multiple times and using time series data, the accuracy of the diagnosis can be improved.

This process is effective because the circadian rhythm is contained in the biological information. For example, it is well known that the growth rate and photosynthetic rate fluctuate, even under constant light and temperature conditions. Therefore, it is preferable to extract the characteristic quantities, such as the amplitude and period, from the circadian rhythm; using this as an index of seedling diagnosis effectively improves diagnostic accuracy. Fig. 26.2A shows an example of measurement using the (AtCCA1:LUC) transgenic lettuce circadian rhythm germination period. Even in continuous light conditions, the circadian rhythm is formed with rooting.

The following is a summary of the diagnostic method. In the seeding and greening process, sprouting is carried out in a dark room for 2 days, and then greening is performed for 4 days with an LED light. On the last day of the greening process, the diagnosis of seedlings is performed. Inspection of 6000 seedlings is carried out on the final day; from these, 5000 are selected as superior specimens. Translocation to the seedling diagnosis system from the greening stage is performed by a shuttle robot that was newly developed for this project (Fig. 26.2B).

The seedling diagnosis system consists of a blue LED for chlorophyll excitation and a cooled charge-coupled device (CCD) camera with high sensitivity and high resolution. An automated conveying device carries a germination panel into the dark box, and the chlorophyll pigment of the plants is excited by the blue LED light. The fluorescence emitted from the chlorophyll is captured every 4 h, six times per day (Fig. 26.2C).

The size and shape of the individual plants are also measured. From the time series data of the six points per day obtained using this method, the size, shape, chlorophyll fluorescence intensity, circadian rhythm, and cycle of the circadian rhythm are calculated. The suitability of the seedlings is quantified by a predetermined evaluation function using these data.

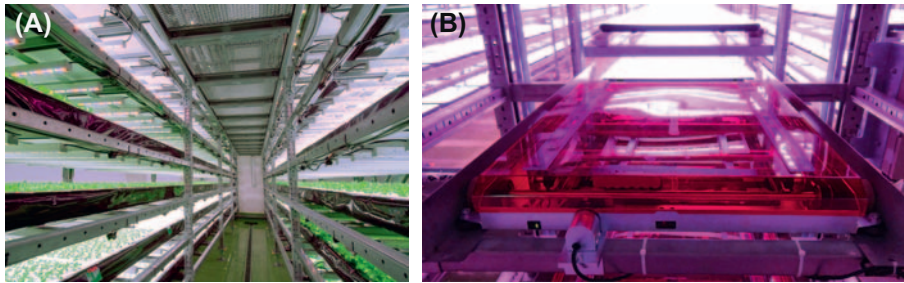
**FIGURE 26.2**

Seedling selection robot system. (A) Example of the circadian rhythm of a transgenic lettuce, (B) shuttle robot system, (C) chlorophyll fluorescent image, and (D) transplant robot.

The aforementioned diagnostic tasks are carried out continuously for 24 h. The suitability characteristics are assigned to all individual specimens immediately prior to sorting. The identification (ID) numbers and evaluation values assigned to all individual seedlings are automatically transmitted to the transplant robot (Fig. 26.2D), and the 5000 seedlings that are determined to be superior specimens are relocated to a nursery panel.

26.4 Shuttle-type transfer robot

In the PFAL of Green Clocks Co., one lane (with a width of 1.5 m and a length of 27.9 m) consists of 36 cultivation units (one unit consists of a cultivation panel and tray) arranged in a row; these have 104 lanes (16 multistage: two rows; 18 multistages: four rows) (Fig. 26.3A). Therefore, the total number of cultivation units is 3774. Two cultivation panels filled with seedlings after the nursery stage are carried to the upstream side of each lane. All units are moved to the downstream side two by two every day and are harvested at the other end of the lane after 18 days. This operation is performed daily. Then, plants of two units are harvested daily, and so the total production is 5200 plants per day.

**FIGURE 26.3**

(A) Multistage cultivation shelves and (B) shuttle-type transfer robot.

Table 26.1 Specifications of a shuttle-type transfer robot.	
Length	700 mm
Width	692–696 mm
Height	765 mm (fully lifted: 96.5 mm)
Weight	22 kg
Mobile velocity	2.9–14 m/min
Lifting height	20 mm
Conveying weight	10 kg
Functions	Self-propelled, battery powered Four-wheel timing belt drive Wireless communication Automatic charging function

A shuttle-type transfer robot is used to move the cultivation panel (Fig. 26.3B; Table 26.1) for the following reasons: for safety, as the cultivation shelf is 7.8 m high; to achieve unmanned operation to minimize the amount of bacteria in the production area; and to reduce labor costs.

The shuttle-type transfer robot is installed to move under the cultivation unit of each lane. For specific operation of this robot, there is a space of two cultivation units at the downstream end of the lane after the daily harvest operation.

The robot moves to the bottom of the cultivation unit (third from the end), and a cam mechanism and built-in motor elevate the tabletop of the robot by 20 mm. As a result, the cultivation unit is lifted up.

The robot moves to the lane end in this state and lowers the tabletop; then, the cultivation unit is set into position. All cultivation units are repeatedly moved by this operation, and free space for two cultivation units can be created in the upstream side of each lane. Two new cultivation units filled with seedlings after the nursery stage are carried to this space.

Because it is inefficient to use the shuttle-type transfer robot in each lane, a lifter that moves the robot vertically is set up at the end of the lane in order to transfer the operation to more than one lane by one shuttle-type transfer robot. In addition, because the robot is battery powered, it is programmed to return to the charging station to charge its battery after the daily transfer task.

**FIGURE 26.4**

Cultivation panel washer.

26.5 Cultivation panel washer

A time-consuming operation in the vegetable production process in a PFAL is washing the trays and cultivation panels. The amount of blue-green algae, which is a type of phytoplankton, increases when light falls on the nutrient solution. As a sharp increase in phytoplankton worsens quality, PFALs are not designed for a large amount of light to be irradiated directly onto the nutrient solution.

However, sowing urethane sponges are included in the nutrient solution, and light directly hits the sponges during the early stage of cultivation. The population of blue-green algae increases in such a situation and adheres to the holes of the cultivation panel.

Washing the cultivation panels and trays after cultivation is essential because the dirt on them breeds bacteria. In large-scale cultivation, such as 218 panel harvests every day, automatic cleaning equipment has been introduced to reduce time-consuming hand-washing (Fig. 26.4).

The device is passed along the trays and panels, and a cylindrical brush rotates like a car wash and washes each panel in approximately 40 s.

Reference

Ogura, T., 2011. Operation should be automated and not so in plant factory for leafy vegetables. *J. Shita* 23, 37–43.

Life cycle assessment

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27.1 Standard of life cycle assessment (LCA)

27.1.1 Introduction

The life cycle assessment has become a useful tool for quantifying the environmental impacts and potential impacts based on a product's life cycle from raw material acquisition through to production, use, and end-of-life treatment (recycling and final disposal), i.e., cradle-to-grave. For example, a photovoltaic power generation system can supply electricity without any inputs of fossil fuels or other materials. However, energy and materials are required for its production, maintenance, and waste treatment. The environmental impacts attributable to such inputs throughout the system's life cycle must be taken into account. Biomass-derived resources can be a renewable resource, but energy for transportation and cultivation, as well as fossil-based fertilizers, may be required. Although the carbon contained in biomass can be regarded as fixed carbon taken from the air, the net carbon balance including the production of such inputs should be taken into account. Air conditioners consume energy when adjusting the temperature and moisture of a room. The environmental impacts during the life cycle of an air conditioner are dominant in the use phase, which means that the efficiency of an air conditioner, i.e., the coefficient of performance (COP), may be the most sensitive parameter for assessing the environmental impact. These topics can be discussed based on the LCA results, and thus the environmental aspects of a product or service can be accurately analyzed and interpreted in the decision-making process.

The role of the LCA, which is defined in ISO 14040, is to clarify the environmental aspects of a product or service throughout its life cycle. The LCA can help identify the points in a life cycle to be improved from the viewpoint of environmental performance, and thus assist decision-makers in industry, government, or other organizations in designing a system or determining a strategy. At that time, the relevant parameters and indicators on environmental performance can also be specified. The results of LCA can be used for marketing products or services in the form of an ecolabel or environmental product declaration. As described in ISO 14040/44, the LCA consists of four phases: goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation, as shown in Fig. 27.1. Various textbooks on the LCA process have been published worldwide, by authors such as Bauman and Tillman (2004) and de Haes et al. (2002).

27.1.2 Goal and scope definition

The “goal and scope definition” phase sets the objective and conditions for the LCA. The system boundary, functional unit, and impact categories are specified before collecting any data. The system boundary is the target scope of the LCA and includes the unit processes to be evaluated. For example, crude oil sourcing may or may not be included in the system boundary based on the existence of any changes in that process. If the same amount of crude oil is used in the scenario comparison, it can be excluded. The system boundary should be set considering the functional unit at the same time. Functional units are the basic common aspects of products or services to be compared in the LCA, for example, the production of a car, 1 kilogram of chemicals, transportation of a person for a distance of 1 km, 1 day of living in a house in Japan, and so on. Fig. 27.2 shows an overview of the system analysis in LCA considering the functional unit with examples for products 1 and 2. Product 1 has the functions A, B, and C, while product 2 has only functions A and B. For example, three-color pens and two-color pens have the same aspects as products 1 and 2, respectively. To compare these products, the difference

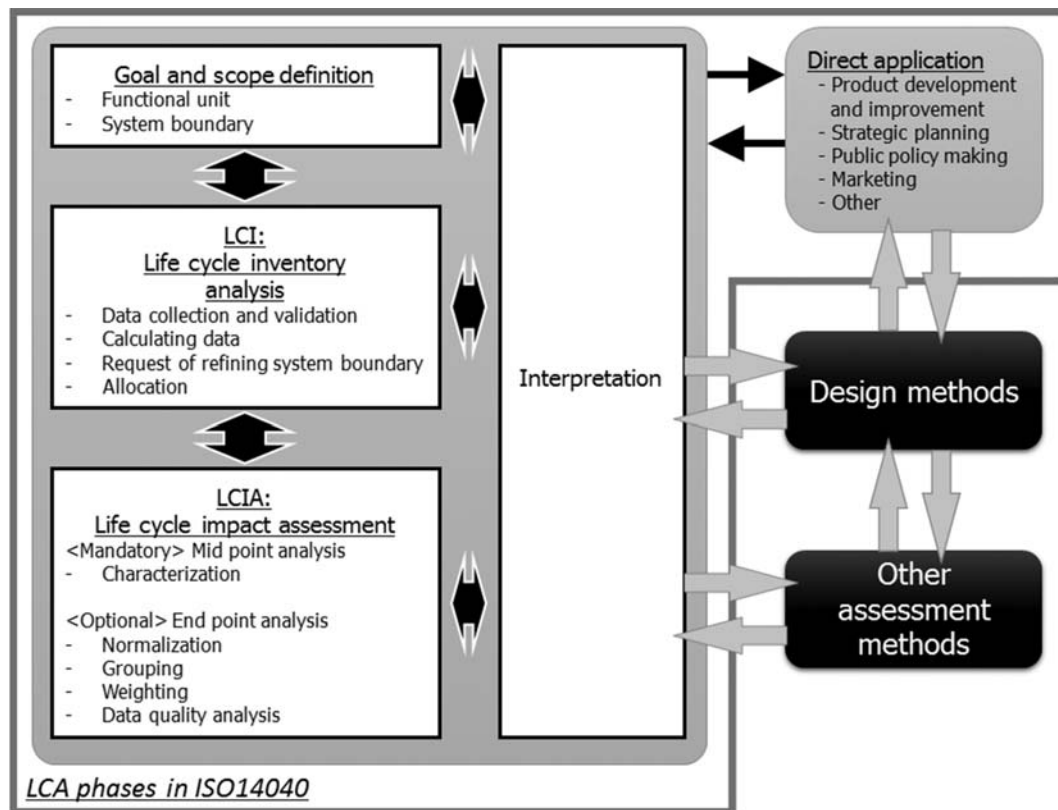
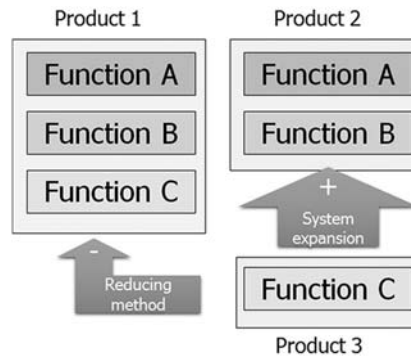


FIGURE 27.1

System design and assessment of the LCA phases in ISO 14,040.

**FIGURE 27.2**

System analysis in LCA considering functional unit.

in functions must be addressed. A third product with only the missing function C can be taken into account in this comparison. The system should be expanded to include this product or save the same amount of environmental load as product 3 in that of product 1. Hence, the system boundary may be modified, to adjust the functional unit.

As mentioned above, the premises and conditions are set in the goal and scope definition phase. In this regard, the phase may be conducted using feedback information from other phases through interpretation. As shown in Fig. 27.1, the boxes are connected by multidirection arrows. This means that the phases can be iterated if necessary. For example, the single-use plastic bags used when buying products can be reused as waste bags in Japan, which means that purchased waste bags must be consumed and therefore considered in the system boundary of their life cycle. In addition to the system boundary and functional unit, the settings for investigating inventory data should also be specified, as introduced below. The impact category in the assessment is also an important setting. As shown in Fig. 27.1, ISO defines a complete LCA as the quantification of environmental impact through a characterization step, in other words, a midpoint analysis (see also Section 27.1.4).

27.1.3 Life cycle inventory analysis

The “life cycle inventory (LCI) analysis” phase quantifies the total environmental load generated within the life cycle stages defined in the goal and scope definition. The procedure to collect inventory data starts based on the data requirements for each life cycle stage, especially the type of data: foreground or background. Foreground data are directly attributable to the target products, while background data can be extracted from spatial or temporal averages. For example, the detailed pathway of consumed electricity from the power generation plant to the transmission or distribution lines must be investigated to obtain the foreground data for 1 kWh of electricity in the system boundary, while the average data from a database can be used for the background data. Generally, the production data for the target products or services may be investigated as foreground data to quantify the environmental load. The grid power data may be extracted from a database even if they are consumed in the foreground processes. Put another way, the foreground data are the data for the foreground processes that are under the control of the decision-maker and for which an LCA is carried

out. Note that the definition of foreground and background data is more complicated in an actual LCA study. Please refer to textbooks specifically on LCA.

Inventory data are available by converting on-site process data, in other words, the operation results. For example, energy and materials are consumed in a process, e.g., [J/month] or [kg/month] to produce the product, e.g., [kg/month]. At this time, the inventory data can be obtained by dividing the input energy and materials by the output products, e.g., [J/kg-product] or [kg-input/kg-product].

Various databases have been developed and opened to the public, such as ecoinvent ([Swiss Center for Life Cycle Inventories](#)), ELCD ([EU-JRC-IES](#)), and JLCA-LCA ([JLCA](#)). Each database has life cycle inventory data sets, with different properties depending on the geographical or temporal applicability, qualities, and the boundary of the data set. In extracting data from the database, such differences in the data sets should be carefully taken into account. Existing LCA software tools such as SimaPro ([PRé Consultants](#)) or MiLCA ([JEMAI](#)) can provide support for LCA practitioners.

27.1.4 Life cycle impact assessment

The “life cycle impact assessment” (LCIA) phase quantifies the environmental impacts by multiplying the results of the LCI analysis [mass environmental load/functional unit] by the impact factors [environmental impact/environmental load]. As an example, the impact categories and their endpoints, areas of protection, and single index are shown in [Fig. 27.3](#), which is the updated life cycle impact assessment method based on endpoint modeling (LIME2) ([Itsubo and Inaba, 2010](#)). As discussed earlier, based on [Fig. 27.1](#), the characterization of environmental impacts is stipulated in the ISO standard. The fate and exposure analyses for environmental loads can be addressed using characterization factors quantified in LCIA methods or other standards. For example, the global warming potential (GWP) is one of the major indicators for climate change, which was originally quantified in the technical reports of the Intergovernmental Panel on Climate Change (IPCC). In addition to the characterization, the damage to areas of protection (AoP) can be quantified using damage factors determined by various analyses. For example, the damage to human health has been quantified through research and investigation, such as epidemiological studies, on the dose–response relationship for chemical substances. Disability-adjusted life years (DALYs) has been adopted as an indicator of human health in some LCIA methods to integrate different types of endpoints attributable to damage to human health. In addition to this endpoint analysis, integration is an optional procedure in the LCIA phase. In LIME2, the indicators on environmental impacts are aggregated into the LIME indicator, which is represented as an economic value, i.e., JPY.

As mentioned above, the LCIA can decrease the number of indicators by analyzing the mechanisms of adverse effects caused by environmental impacts. This may avoid some of the trade-off relationships between environmental impacts. In this regard, however, the meaning of each indicator such as the emission amount of carbon dioxide or the consumption of phosphorus resources must be carefully interpreted in terms of improving the target system.

27.1.5 Interpretation

The “interpretation” phase has two important roles in the intermediate or decision-making stage of the LCA. In the intermediate stage, a tentative result or situation may be returned to the goal and scope definition phase as feedback requesting redefinition of the LCA conditions. Expansion of the system

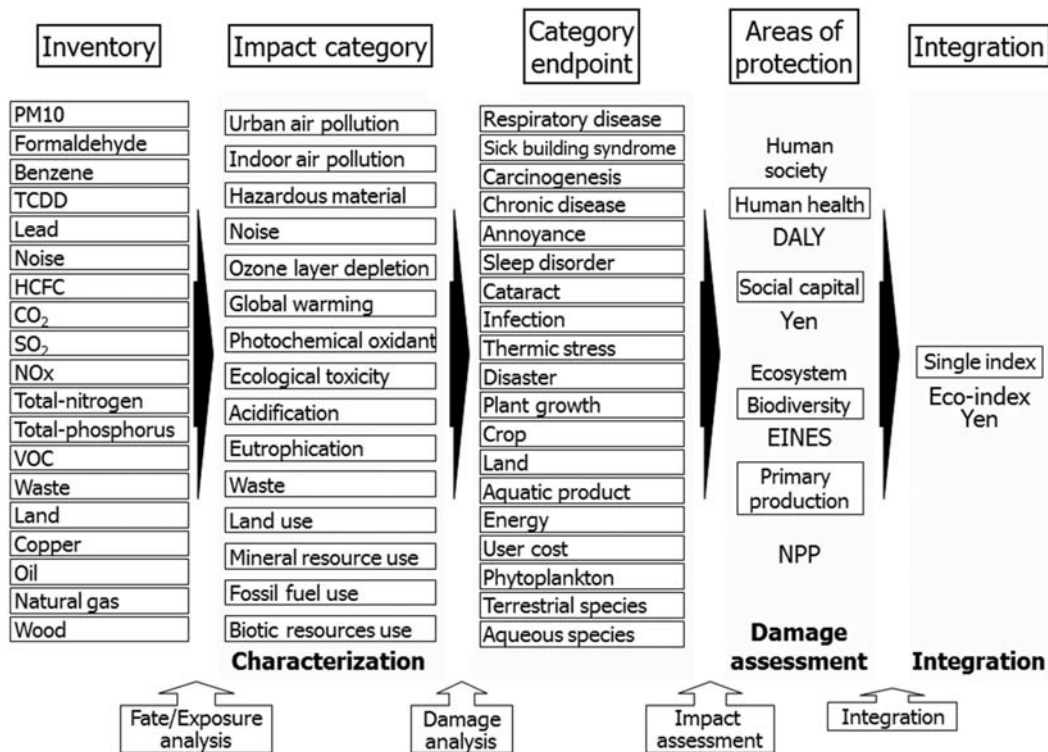


FIGURE 27.3

Overview of LIME2 (Itsubo and Inaba, 2010).

boundary, for example, can be considered based on such feedback. Impact assessment methods can also be reselected based on the available impact factors. The LCA practitioners should be able to determine the necessity of such redefinition by checking the intermediate outcomes from the LCA study. In the decision-making stage, on the other hand, “direct application” of the LCA results must be taken into account, at which point practitioners should be able to understand all phases of the LCA, existing uncertainties in the quantified LCI and LCIA results, and so on. There may be tradeoff relationships between environmental impacts, which can also be found in the analysis with other aspects such as economic or social ones. Multiobjective decision-making is essential in designing the actual system framework (Sugiyama et al., 2008; Kikuchi and Hirao, 2009).

27.2 General remarks for the assessment of PFALs

An example of the life cycle of PFALs (plant factories with artificial light) and their products is shown in Fig. 27.4. Plant and product life cycles intersect with each other at the manufacturing stage. An LCA study on PFALs should consider these two types of life cycles. In the following sections, the points to be taken into account are overviewed. At this time, the goal of the LCA is assumed to be the PFAL design.

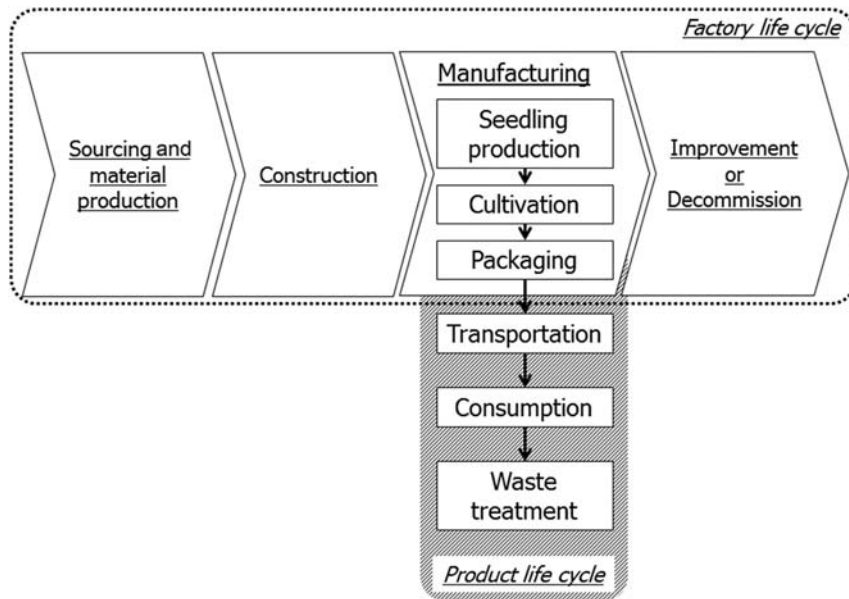


FIGURE 27.4

Example of the life cycles of indoor farms and products.

27.2.1 Inventory data collection/impact assessment

Construction and manufacturing data on the PFAL should be collected as foreground data. As the construction of a factory, base metals and materials such as steel and cement are taken into account. The factory exterior and interior must be considered as required inputs for the construction, as shown in Fig. 27.4. The cumulative production data on each input metal and material can be background data, when special data are not used, e.g., local ecomaterials, reuse of existing buildings, or construction waste.

As for the processes supplying energy, the sources of energy should be carefully taken into account, for example, some factories install photovoltaic (PV) power systems or other distributed energy technologies for their own processes. The environmental load originating from the installation of such technologies must be considered as foreground data, because the initial environmental load for installing energy technologies is highly sensitive to their operation ratio. The life time or actual usage years of the technologies is also highly sensitive to the total environmental load.

Regarding the operation data, as well as energy supply, the fertilizer conditions are also important and should be carefully examined. Especially, the impacts of using resources on the phosphorus or nitrogen cycles are one of the most important topics in agriculture. In the flow of materials, phosphorus is consumed without an effective recycling system (Matsubae et al., 2011), and is an important and essential constituent of fertilizers. If resources ran short, fertilizers could not be produced and the capacity for food cultivation might be seriously reduced. Thus, the efficiency of using phosphorus, i.e., the amount of phosphorus consumed per unit production, must be carefully checked and assessed. In a comparison with general farming, the LCA study of indoor farming should also take into account the inventories of land use, such as area, time of occupation, or existence of transformation. The types of

impacts on land use include GHG (greenhouse gas) emissions from the soil, or other emissions. Meanwhile, the products from PFALs, such as lettuce, are cultivated in clean rooms. This means that there is no loss of lettuce before eating because even the outermost leaves are clean, whereas vegetables grown outdoors often lose leaves due to dirt. Such differences should be taken into account by including the use or consumption phase of products.

27.2.2 Functional unit

Indoor farms can play a number of roles in agriculture. Even though the most commonly useable functional unit is the production of agricultural products, multiple functions should be considered for comparison with outdoor cultivation: stable production even under severe weather such as typhoons, heavy rain, low temperature, and so on, or considerably high productivity on land or water, and fertilizer use. Some of these points can be quantified by the LCA as environmental impacts such as resource depletion. However, it is not easy to consider all aspects of indoor farming using a general LCA. For example, the LCA generally uses steady-state LCI data. The stability of production against severe weather can be an indicator of the risk hedge for such events. The precautionary function must be addressed by setting the goal and scope of the LCA study.

27.2.3 Interpretation

In the interpretation phase, LCA practitioners should take into account not only the results of the LCA, but other aspects as well. For example, indoor farms could become a new and huge user of power on the power grid. Because power from variable renewable energy sources such as PV and wind may cause non-negligible fluctuations in power resulting in limited usage during a shortage, indoor farms could serve to stabilize the supply and demand for power by changing the power load through energy storage. Indoor farms could also effectively utilize unused waste heat from other manufacturing plants such as plastics molding, food processing, or other production processes. The efficiency of resource consumption could be increased by using low-temperature heat. In urban areas, indoor farms can provide work for elderly people. These points cannot be easily addressed in the LCA. Therefore, the required assessment methods should be integrated at this phase and a final decision should be carefully made.

27.3 A case study of LCA on plant factories (Kikuchi et al., 2018)

A case study of LCA on plant factories was conducted by Kikuchi et al. (2018). The PFSL and PFAL examined in this section were demonstration factories located at Chiba University in Kashiwa, Japan (ChibaU_PFs), where long-stage, high-density cultivation and a 10-stage vertical horticulture system were used to produce fresh tomatoes and lettuce in hydroponic culture using rockwool and polyurethane, respectively, as the culture media. The designed yields and cultivation areas for ChibaU_PFSL and ChibaU_PFAL are 55 t/(10a·y) with 1782 m² and 2950 stems/day with 338 m², respectively. Note that the results shown in this section were taken from the literature (Kikuchi et al., 2018). This section summarizes the results by referring to the detailed settings and results of the technology assessments on plant factories shown in the literature.

27.3.1 Settings: indicators

Life cycle (LC) GHG emissions, fertilization with NPK nutrients, and water use and consumption were used as assessment indexes, the detailed settings of which are explained below. LC-GHG is quantified by

cradle-to-gate LCAs of vegetables. Fossil-fuel-derived GHG emissions are accounted for by LC-GHG with global warming potential in the fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC, 2007). Because the methods for resource extraction are limited to considering NPK nutrients simultaneously, the total material requirement (TMR) (European Environment Agency, 2016) was adopted as the indicator on the use of N, P₂O₅, and K₂O (Yamasue et al., 2013) for fertilization (Yamasue et al., 2015), which can indirectly evaluate the resource extraction loads by quantifying the total mass processed to obtain the products. Water input or water withdrawal can be classified as consumptive use, i.e., water consumption, and degradative use, i.e., water use (Pfister et al., 2009). Water use and water consumption (Reig, 2013) were calculated in this study considering the differences between blue and green water (Water Footprint Network, 2017). The water consumption in background processes was also extracted and accumulated based on the applied LCI databases explained below. In addition, the land use for farming was also adopted as an assessment index, which implies the productivity of vegetable cultivation of conventional horticulture systems and ChibaU_PFs.

27.3.2 Settings: life cycle boundary and functional unit

The life cycle boundary defined for the ChibaU_PFs is illustrated in Fig. 27.5 considering the overview of the farming process system. The boundary can be schematically divided into four phases: design and construction, operation, maintenance, and decommissioning. The vertical direction describes the flow of agricultural processes in the life cycle. The horizontal direction includes the main flow for the materials input to or output from the processes within the four phases. The cradle-to-gate life cycle

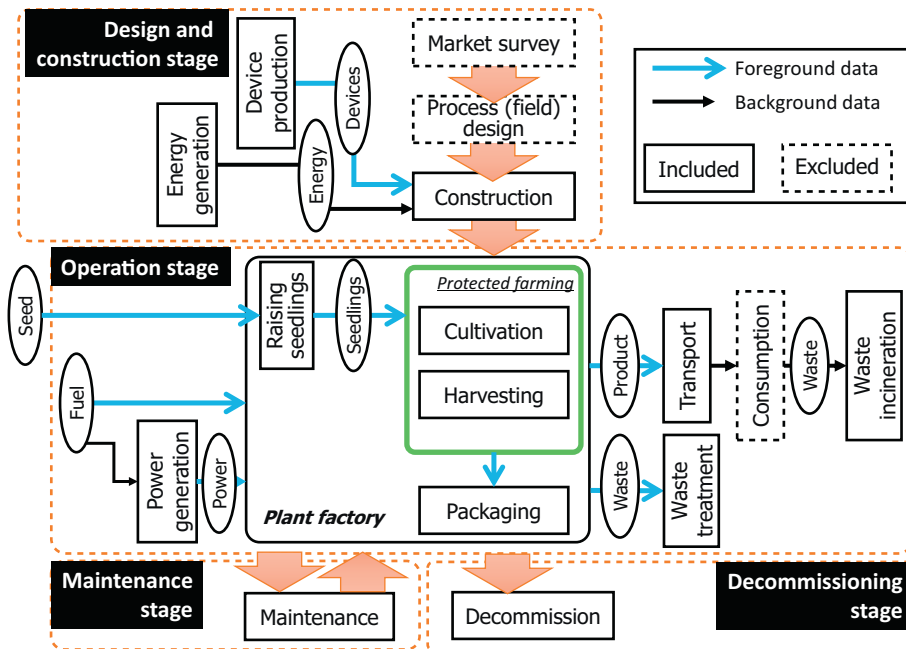


FIGURE 27.5

Life cycle boundary examined in the case study of LCA for plant factories.

processes for vegetables are included in the horizontal direction of the operation phase. The processes for market survey and process/field design are not directly included in the assessment, but should be reconsidered with the assessment results to adjust the scale of cultivation. The environmental impacts induced by the construction processes are allocated to unit amounts of production based on the lifetime of buildings and devices, including decommissioning. The consumption, i.e., eating, of the produced vegetables is the same in all cases including conventional horticulture and the ChibaU_PFs.

The functional unit for the LCA of plant factories and conventional horticulture systems was set as the production of vegetables represented by one tonne of products and productivity, i.e., 1 t/(10a · y), as reference flows to consider the viewpoints of consumers and suppliers. The same quality of fresh tomatoes as produced by Japanese conventional horticulture systems was produced in the ChibaU_PFSL, which was proven when they received the same classification of unit tomato prices in the market as those from conventional systems.

27.3.3 Settings: data for assessments

All inputs and outputs were investigated as foreground data of the ChibaU_PFs for the LCI analysis. The data were extracted from automatically logged and manually stored records covering approximately 2 years from 2012 to 2014, in which the inventories on construction and operation are respectively organized. The lifetime of plant factories and all installed devices was assumed to be 15 years, except for expendable items such as cultures, fluorescent lighting, and plastic film. The lifetime of such expendables was set as 2 years for cultures in both ChibaU_PFs, 5 years and 3 years for fluorescent lighting in ChibaU_PFSL and ChibaU_PFAL, respectively, and 5 years for polytetrafluoroethylene in ChibaU_PFSL. General maintenance was also included in the extracted total foreground data, such as the water and electricity required to clean the floors and equipment in the factories. Fertilization with NPK nutrients was obtained as the amount of N, P₂O₅, and K₂O fertilizers applied. While the PFAL uses only city water to avoid fungus contamination in the cleanroom environment, the PFSL prioritizes the use of rainwater, followed by underground water and city water. Rainwater from the roof is collected in tanks and pumped to the hydroponic systems through filtration. The water containing nutrients is circulated in the cultures and other water is added to compensate for water lost through evapotranspiration and output as waste and products. In this regard, ChibaU_PFAL circulates the water condensed by an air conditioner, which means that part of the evapotranspiration can be recycled. All required background data were extracted from public LCI databases (JEMAI, 2017; ecoinvent, 2014).

For conventional horticulture systems, site-specific fertilization data and yields were extracted from Japanese prefectural statistics for 2013 (MAFF, 2015a, 2015b). The cradle-to-gate LC-GHG caused by the cultivation of tomatoes and lettuce was retrieved from an LCI database (JEMAI, 2017) with a difference in prefectures. The application of NPK fertilizers generally conforms to local farming guidelines. The effects of fertilization, in units of kg-product per kg applied fertilizer, also referred to as the partial factor productivities of applied fertilizers (Cui et al., 2014), can be calculated by dividing the yield [kg-product/(10a)] by the fertilization [kg-fertilizer/(10a)] in prefectural statistics (MAFF, 2015a, 2015b). The data on water use and consumption in conventional Japanese horticulture systems were estimated basically by applying the guidelines for computing crop water requirements (Allen et al., 1998) with the reference crop evapotranspiration with meteorological conditions (NIAES, 2016), cultivation schedules (MAFF, 1998), irrigation efficiency (JSIDRE, 2000), and the cultivation statistics (MAFF, 2015b) for tomatoes and lettuce in Japan considering blue or green water use (Ono

et al., 2015). The values of fertilizer use, water use, and water consumption vary widely among prefectures.

27.3.4 Settings: applied energy technology options

Technology options that allow the effective use of energy were considered as alternatives to business as usual: the current operation of the ChibaU_PFs (labeled in the results as the Base case). The options considered for the ChibaU_PFs were the utilization of unused heat, a solid-oxide fuel cell, PV power, improved electric devices such as heat pumps and lighting, and the installation of all options (All options). These technology options are at different levels of development and require estimation of the inventories.

27.3.5 Results and discussion

The simultaneous and quantitative analyses of multiple aspects of plant factories and conventional horticulture systems enable an integrated interpretation of the applicability of plant factories for food sustainability management. As shown in Fig. 27.6, the ChibaU_PFs have the potential to reduce land use, water use and consumption, and NPK resource impact; instead, they have increased GHG emissions, which can be mitigated by the synthesis of energy technology options. Based on the analysis results, they can help intensify domestic cultivation and mitigation of water requirements in an increasingly globalized world (Wang and Zimmerman, 2016), even in countries without sufficient precipitation or fertile land for agriculture. These values can be regarded as performance indicators of plant factories within the nexus of food, water, and energy. According to the results of the ChibaU_PFs, such facilities could save water and nutrients with increased food production at the cost of higher energy input. Although PFSLs have greater advantages than PFALs based on these indicators, the location of a PFSL is limited by the appropriate sunlight intensity.

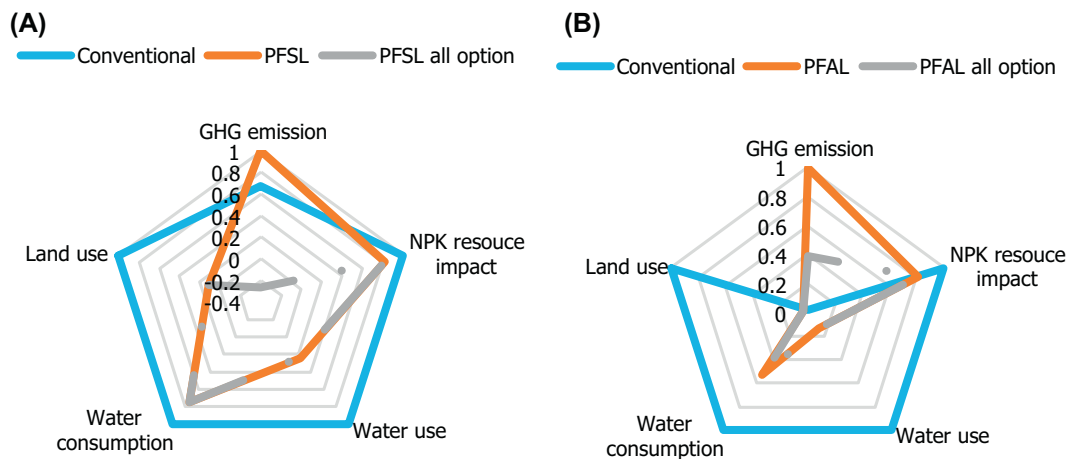


FIGURE 27.6

Example of LCA results in the case study shown as a radar chart of indices for the “Base case” and “All options” of the ChibaU_PFs, the values of which are normalized with respect to the maximum value of an indicator set to 1. (A) PFSL, (B) PFAL.

27.4 Summary and outlook

The LCA can quantify the environmental impacts of a product or service by analyzing the inventories of the processes included in the target life cycle. Because the LCI inventory database facilitates the collection of inventory data, practitioners can conduct an LCA by investigating important foreground data. Impact assessment methods enable the practitioners to consider direct and indirect effects of environmental loads from the target life cycles. The system boundary and functional unit have many points requiring interpretation, which means that various types of assessment can be performed by setting appropriate conditions.

The LCA has some limitations in terms of the framework characteristics and data availability. For example, the settings for the system boundary and functional unit should be decided by the practitioners, which may result in subjective decisions even though such settings can make a large difference in the results. The LCA includes a critical review stage to check such subjectively decided settings or parameters, justify unavoidable assumptions, and approve the transparency and completeness of the LCA study. This review stage can improve the limitations of the LCA. On the other hand, the system dynamics and nonlinearity of the process inventory and environmental impacts are examples of aspects that are difficult to consider in the LCA. Such limitations must be taken into account by LCA practitioners. Note that the limitations and unresolved problems in the LCA have been discussed elsewhere (e.g., [Reap et al., 2008a, 2008b](#)).

Through a case study of LCA on existing plant factories, their key concepts were examined. Multiple aspects of food production, i.e., NPK fertilizers, water use and consumption, and GHG emissions for a plant factory with sunlight (ChibaU_PFSL) producing fresh tomatoes, and a plant factory with artificial light (ChibaU_PFAL) producing lettuce, were examined and compared with that of conventional Japanese horticulture systems. Although we used existing evaluation methods, including LCA, for these multiple aspects, the simultaneous analyses enabled an integrated interpretation. We demonstrated that the examined plant factories reduced the use of irreplaceable resources for food production, i.e., phosphorus, water, and land area, at the cost of additional energy consumption. By employing emerging energy technology options, energy consumption can be sufficiently reduced to be competitive with that of conventional horticulture systems. The results indicate that plant factories could become a viable or competitive production technology, changing the factors in the nexus of food, energy, and water systems.

In the evaluation of indoor farming by LCA, the various functions achievable by technology should be taken into account. As well as the quality of products, that of the processes as a source of food, e.g., production stability, adaptivity to climate, high productivity on land, water, and fertilizer, must be addressed as differences from cultivation in open farming. At the same time, technology development should also be considered as a parameter sensitive to the final results of LCA. Lighting, insulation, air conditioning, and control technologies are now under development. The efficiency of indoor farming can be improved in the future using such developed technologies. Not only the LCA, but also other assessment methods should be incorporated into the decision-making process. Even in the LCA-related methods, life cycle costing and social life cycle assessment ([UNEP/SETAC Life Cycle Initiative, 2009](#)) are also elements of life cycle sustainability assessment ([UNEP/SETAC Life Cycle Initiative, 2011](#)). Making informed choices on products and processes is strongly needed and can be supported by LCA.

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Education, training, and business workshops and forums on plant factories

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List of Abbreviations

ANTS	Active-sensing Networks and Tel-existence System
GECS	Greenhouses with environment control systems
JPFA	Japan Plant Factory Association
MAFF	Ministry of Agriculture, Forestry and Fisheries
PFALs	Plant factories with artificial lighting
TEPCO	Tokyo Electric Power Company
UECS	Ubiquitous environmental control system

28.1 Introduction

With the rapid increase in the number of plant factories, pressing issues have emerged such as technical and operational challenges, inadequate business plans, and shortage of human resources. On the other hand, development is progressing on new technologies and utilization methods for plant factories and further expansion is expected.

As of the end of January 2018, JPFA membership comprised 124 companies and 98 individuals. JCPA has been holding workshops to share the latest information with members and nonmembers, and forums to train people in technical and management skills on solar type plant factories or semiclosed plant factories defined as greenhouses with environment control systems (GECSs) and completely closed plant factories defined as plant factories with artificial lighting (PFALs).

The following committee members discuss and organize the composition and contents of the workshops and forums based on the latest issues and new technologies:

Chairman: Yutaka Shinohara, Professor Emeritus of Chiba University
 Member: Toyoki Kozai, Professor Emeritus of Chiba University, Honorary President of JPFA
 Member: Toru Maruo, Professor at Chiba University, Vice President of JPFA
 Member: Satoru Tsukagoshi, Associate Professor at Chiba University
 Member: Sachiko Toi, JPFA

Lecturers and trainers include researchers from universities and research institutes, industry engineers, managers and administrators, Ministry of Agriculture, Forestry and Fisheries (MAFF) government officials, prefectural government officials and researchers, JPFA members and staff, and others.

28.2 JPFA business workshops

JPFA carries out monthly workshops on a wide range of issues pertaining to plant factory business. From October 2009 to March 2018, a total of 118 workshops were held with 9109 people attending. The objective of the workshops is to share and discuss the latest information on the science, technology, markets, business, and operation of plant factories. The following is an overview of the workshops held, from the first one to the most recent.

1. Direction of Chiba University's plant factories (Oct. 1, 2009)
 - Issues and aims of plant factories at Chiba University
 - Concept of 21st century plant factories
2. System of hydroponic culture (1) (Oct. 8, 2009)
3. Heat pumps (Oct. 20, 2009)
 - Reduction of CO₂ emissions through the application of heat pumps to agricultural fields, and efforts of Tokyo Electric Power Company (TEPCO)
 - Examples of applying heat pumps to greenhouse horticulture
 - Heat pump/air-conditioning system for greenhouses proposed by Mitsubishi Electric Co.
4. System of hydroponic culture (2) (Oct. 30, 2009)
 - Basic hydroponic culture course for beginners—nutrient components
 - Outline of main hydroponic culture methods and medium
 - Basic structure of hydroponic culture system
5. Progress of development of greenhouse horticulture and environmental control technology in the Netherlands (Nov. 19, 2009)
 - Covering materials, screens and lamps to control crop growth and quality
 - How to achieve high-yield tomato production (100 kg/m² or more per year)
 - Production at low-energy input facility
6. Ubiquitous environmental control systems (UECS) (Dec. 3, 2009)
 - Features and functions of ubiquitous environmental control system (UECS)
 - Concept of a system to analyze and examine plant factory operations
7. Light sources in PFALs (Dec. 17, 2009)
 - Outline of plant factories and future prospects
 - Importance of cultivation software in plant factory business
 - Future of LEDs in plant factory markets
8. Plant breeding for plant factory cultivation (Jan. 14, 2010)
 - Direction and potential of tomato breeding for hydroponic culture
 - Current situation of lettuce breeding and possibility of exclusive variety for plant factories
 - Lettuce (catalog)
 - Current situation of lettuce for hydroponic culture and the direction of breeding
9. Vegetable processing and distribution (Jan. 21, 2010)
 - Introduction of Wagoen Agricultural Cooperative
 - Expectations for fresh vegetables
 - Opportunities for plant factories as seen by the processing and distribution industry
 - Expectations and current efforts for urban plant factories

10. Integrated pest management in plant factories (Feb. 4, 2010)
 - Tomato insects in greenhouse horticulture, and low-pesticide management technology
 - IPM (plant disease) in plant factories
 - Actual conditions of the method for controlling moths by light, and development of a new cultivation technique to control moths by lighting
11. Selection of light sources and designing the lighting and air-conditioning for PFALs (Feb. 18, 2010)
 - Light source in plant factories with artificial lighting (PFALs)
 - Light source and energy/material balance of PFALs
 - Utilization efficiency of electricity, water, and CO₂ in a closed plant production system
12. Issues of high-yield tomato production (Mar. 4, 2010)
 - Issues of high-yield tomato cultivation—issues of longer term and high-wire system
 - Concept of low-shelf/high-density tomato cultivation and challenges for dissemination and expansion
 - Development of high productivity facility environment control technology focusing on carbon dynamics
13. Production in large-scale greenhouses and PFALs in China, production in greenhouses in Saudi Arabia (Apr. 16, 2010)
 - Current situation and ability of greenhouse horticulture in China
 - Greenhouse horticulture/plant factory facilities in China and Saudi Arabia
 - Progress of greenhouse facilities in China and possibility of application to Japan
14. Outline of plant factories at five sites in Japan supported by MAFF (Apr. 26, 2010)
 - Role of plant factories in modernizing greenhouse facilities, and efforts of the Ministry of Agriculture, Forestry and Fisheries (MAFF)
 - Outline of plant factories at Chiba University as a project for demonstration, exhibition, and training supported by MAFF
 - Operations of the project for demonstration, exhibition, and training in a “Model House Type Plant Factory” supported by MAFF
 - Operations of the Plant Factory Research Center at the Osaka Prefecture University 21st Century Science Research Center
 - Outline of plant factories at the National Agricultural and Food Research Organization (NARO)
 - Outline of plant factories in Mie Prefecture
15. Management of hydroponic systems (May 13, 2010)
 - Concept of drip irrigation, basic design of system, how to choose the materials for drip irrigation
 - Control of nutrient solution volume in plant factories—From concentration to quantity
 - Management of nutrient solution—Focusing on nitrogen
16. Integrated environmental control using multipurpose heat pump in a semiclosed production system (June 10, 2010)
 - Heat pump air conditioning
 - Household heat pump—Reduction of primary energy consumption and carbon dioxide emissions for greenhouse heating

- Integrated environmental control and utilization of heat pump in a semiclosed type greenhouse in the Netherlands
- Integrated environmental control of plant factories using multipurpose heat pumps
- 17.** Ubiquitous in-town PFALs (July 8, 2010)
 - In-town plant factories
 - Office “urban farms” with the theme of harmonious coexistence with nature
 - Prospects and challenges of in-town plant factories: resource conservation, environmental preservation, proposing an agricultural life with local production and consumption
- 18.** Expanded opportunities for PFALs (Aug. 5, 2010)
 - Plant cultivation in closed ecosystem experimental facilities
 - Utilization of closed plant factories for production of useful substances
 - Plant factories in space farms
- 19.** Financial balance of PFALs and consultation (Sept. 13, 2010)
 - Marketability of crops from plant factories, and consulting
 - Fostering plant factory vegetables
- 20.** Culture medium for seedling production and growing beds (Oct. 14, 2010)
 - Characteristics required for plant growth medium, and challenges
 - Rockwool as a plant cultivation medium
 - Characteristics and possibilities of urethane medium
 - Organic (peat·cocopeat) medium
- 21.** Issues of ground environmental control (Nov. 11, 2010)
 - Characteristics of cover materials
 - Control of light environment
 - Ventilation and cooling
- 22.** Plant factories and a happy life (Dec. 9, 2010)
 - Livable creations in an aging society, and plant factories
 - Efforts of the Universal Farm to work with persons with disabilities
 - Flower cultivation business in an Oriental Land subsidiary
- 23.** Issues of root zone environmental control (Jan. 13, 2011)
 - Composition and concentration control of nutrient solution
 - Why do crops grow faster when hydroponically cultivated compared to traditional soil cultivation?
 - Underground environment and plant growth—A viewpoint on utilizing factory production
- 24.** Outcomes and plans for plant factories: Greenhouse with environmental control system (GECS) at Chiba University (Feb. 17, 2011)
 - Productivity improvement through integrated environmental control
 - Long-term/high-wire system for tomato production
 - Next-generation type tomato production system
 - Progress report: MKV’s GECS—Low-pesticide/high-yield/single-truss/moving bench/high-density tomato cultivation system
 - Progress report: Daisen’s GECS—D-tray/low-shelf/high-density tomato cultivation system

25. Outcomes and plans for plant factories: PFAL, in-town PFAL and “Interthematic Area” consortiums (Mar. 10, 2011)
 - Low-cost future PFALs
 - Stable lettuce production in PFALs
 - In-town plant factory consortium
 - Activities of “Interthematic Area” consortiums
26. Field tour at Sankyo Frontier Co. (Jan. 21, 2010)
 - Newly developed plant factories
27. Field tour at the campus of Chiba University (Feb. 18, 2010)
 - Small heat pump (air conditioner) and stirring fans installed in greenhouses
 - Closed seedling production system
28. Field tour of plant factories at Tamagawa University (July 1, 2010)
29. UECS at the Institute of Vegetable and Tea Science (Aug. 3, 2010)
 - Concept of a ubiquitous environmental control system (UECS) and its advantages
 - Integrated environmental control for high-yield production of tomatoes by UECS
 - Commercial equipment for UECS and dissemination situation
 - Introduction of equipment compatible with UECS (irrigation controller)
30. Field tour of plant factories at Tamagawa University (Aug. 6, 2010)
31. Tomato greenhouse production around the world (Dec. 15, 2010)
 - Key technology in US tomato cultivating facilities
 - Comparison with Japan and Europe
32. Plant factories around the world, current situation in the Netherlands and China (Feb. 17, 2011)
 - Human resource development in the Netherlands
 - Plant factories in China
33. UECS utilization for plant factories at Chiba University and its demonstration (Feb. 23, 2011)
 - UECS and its usage at the Chiba University plant factories
34. Overall introduction of plant factories at Chiba University and their measurement and integrated environmental control (Apr. 14, 2011)
 - Chiba University’s general targets for its plant factories
 - Measurement and integrated environmental control at the Chiba University Botanical Plant Base
35. JA Zen-Noh GECS at Chiba University and information updates on plant factories in China and Korea (May 19, 2011)
 - Progress report: JA Zen-Noh GECS—Tomato/one-truss/high-density/hydroponic cultivation system to achieve profitable agribusiness
 - Current situation in Korea
 - Current situation in China and Taiwan
36. Actual results of construction at Chiba University, learning from failures in other cases, and development of robots supporting agricultural work (June 16, 2011)
 - Expectations and requests for future efforts based on the actual results of construction at Chiba University and failures in other cases
 - Training center—chemical analysis facility at Chiba University
 - Development of robots supporting agricultural work

37. Situation of greenhouse and plant factory production in Fukushima and Miyagi after the Great East Japan Earthquake, and the impact of blackouts and their countermeasures (July 14, 2011)
 - Greenhouse horticulture in Fukushima Prefecture after the Great East Japan Earthquake
 - Damage condition of facilities for greenhouse horticulture and plant factories, etc. in Miyagi Prefecture
 - Influence of blackouts and countermeasures in hydroponic cultivation systems (NFT system)
 - Measures against power failure in hydroponic cultivation systems (D-tray system)
 - Recommendations from the cultivation experts group supporting the damaged area
38. MKV's GECS at Chiba University, seed coating and seedling production (Aug. 8, 2011)
 - Present status and issues of vegetable seed production and seed selection/treatment
 - Present status and issues of seedling production from seedling producers
 - Recent introduction results and issues on "Nae-Terrace," a closed seedling production system
 - Progress report: MKV's GECS—Low-pesticide/high-yield/single-truss/moving bench/high-density tomato cultivation system
39. Plant Factory Research Center on the Matsudo Campus, Chiba University (Sept. 15, 2011)
 - Research center facility overview (Matsudo, Kashiwanoha)
 - Shading of the greenhouse, cooling, supplementary light
 - Greenhouse environmental simulation, growth model for tomatoes and yield prediction
 - Environment control in PFALs
40. Current situation of plant factories in Japan, Daisen GECS at Chiba University, Mushroom production and issues (Oct. 20, 2011)
 - Recent status of plant factories in Japan
 - Progress report: Daisen GECS—D-tray/low-shelf/high-density tomato cultivation system
 - Recent status and issues of mushroom production
41. Recent status of plant factories in Japan, Iwatani Agri Green GECS and Seiwa GECS at Chiba University, Chiba University's efforts on plant factories (Nov. 17, 2011)
 - Recent status of PFALs in Japan—Nisshinbo's PFAL
 - Progress report: Iwatani Agri Green GECS
 - Progress report: Seiwa GECS
 - Household heat pump for horticultural use
 - Aims of the aeroponic system
42. Current situation of plant factories in China (Dec. 15, 2011)
 - Present status and future of plant factory research in China
 - Technological progress in small plant factories and urban horticulture challenges by AgriGarden in China
43. Effects and possibility of green lighting in plant factory production (Jan. 12, 2012)
 - Background of green light effect study
 - Effect of green LED light on growth and useful component accumulation of lettuce and tender green mustard
 - Possibility of using green light in plant factories

44. PFAL, “Interthematic areas,” and “In-town plant factory” consortia (Feb. 9, 2012)
 - Low-cost future type PFALs—Mirai
 - Demonstration/experiment of stable production of head lettuce
 - Progress report: Interthematic areas consortium
 - Progress report: In-town plant factory consortium
45. Activity report for 2011 on “GECS” consortia (Mar. 15, 2012)
 - Improved productivity through integrated environmental control—Seiwa
 - Long-term/high-wire tomato cultivation—Iwatani Agri Green
 - Next-generation type tomato production system—JA Zen-Noh
 - Low-pesticide/high-yield/single-truss/moving bench/high-density tomato cultivation—MKV
 - D-tray/low-shelf/high-density tomato cultivation system—Daisen
46. How to reduce heating expenses in GECS (Apr. 19, 2012)
 - Greenhouse air conditioning concept and measures
 - Characteristics of covering materials and thermal insulation materials
 - Facility structure for efficient air conditioning
47. Measures to counter high temperature in GECS (May 17, 2012)
 - Measures against high temperature using fine fog
 - Importance of external shading and environmental management in facilities
 - Measures against high temperature using internal curtains
 - Summer night cooling by heat pump
48. Forefront of PFAL business (June 21, 2012)
 - Marketing strategy for vegetables produced in plant factories
 - Recent move concerning PFALs
 - Raising seedlings for grafted tomatoes in a closed system—Nae-Terrace
49. Tomato production technique, vegetable grafting outside of Japan (July 6, 2012)
 - Progress in tomato production technology half a century—Progress of facilities, environment, creativity/breeds, management techniques, etc.
 - Present state of vegetable grafting in Europe and the United States—Does Japan capture international business opportunities?
50. Possibility and problems of strawberry cultivation in plant factories (July 19, 2012)
 - Strawberry cultivation under full artificial light in Nisshinbo
 - Fostering seed breeding variety “Chiba F-1” to change strawberry cultivation
 - Super high-yield strawberry cultivation using D-trays
51. Latest environmental measuring control in plant factories (Aug. 23, 2012)
 - Next-generation measurement control system for plant factories (ANTS)
 - Environment and its control in Chiba University’s plant factories
 - Latest CO₂ monitor, controller, and usage method
 - Environment measurement sensors
52. In-town plant factories (Sept. 20, 2012)
 - Service design of plant factory
 - City development of Kashiwanoha’s Smart City and Futuristic Field’s smart network
 - Results of acceptability verification of in-town plant factories
 - Plant factory “Agri-Cube” unit

- Plant factory as teaching material for elementary schools
- Effect of lighting devices using LED made by Philips Co.
- 53.** Business of plant factories (Oct. 18, 2012)
 - Current status and issues of tomato greenhouse production business
 - Business issues in large PFALs
 - Establishment of cultivation technology for high-yield strawberry production (100 tons/ha) and its business issues
- 54.** Health care and plant factories (Nov. 15, 2012)
 - Medical and agricultural cooperative integrated research project at Sakakibara Memorial Hospital
 - Production design and new movement of agromedical foods, standardization of cultivation method by elaborate agriculture
 - Futuristic environmental cities and plant factories
 - Development of fundamental technology for plant-based high-value-added substance manufacturing
- 55.** Quality of vegetables in plant factories (Dec. 13, 2012)
 - Quality of vegetables in plant factories
 - Evaluation method of antioxidant capacity in vegetables and expectations for plant factories
 - “Delica” scores, vegetable evaluation criterion, and plant factory vegetables
 - Value of plant factory vegetables viewed by the market
- 56.** New development of PFAL business (Jan. 17, 2013)
 - What is required for the dissemination of PFALs?
 - Plant factory vegetable certification system—TPAC-PPS third-party certification
 - Establishment of quality, cost, supply, and added value toward expansion of plant factory business—Challenge of clarifying the required specifications of plant factory vegetables
- 57.** Destination of plant factories (Feb. 14, 2013)
 - From plant factories to vertical agriculture, urban agriculture, and agricultural culture city
 - Project of developing an integrated environment control system—Interim report
 - Latest status of plant factory research and development, and dissemination in China and Taiwan
- 58.** Newly established plant factories in the Tohoku district after the Great Earthquake (Mar. 14, 2013)
 - Fully controlled plant factory in Kawachi, Fukushima Prefecture
 - Production and sales strategy for low-potassium lettuce
 - Miyagi Reconstruction Park/PFAL—Supporting the reconstruction of Tohoku and creation of new industries by advanced agriculture
- 59.** Recent trend in GECS: rebuilding project in the disaster area (Apr. 18, 2013)
 - Rebuilding support projects in Watari and Yamamoto areas
 - Role of the Granpadome in regional rebuilding
 - Design standards and demonstrating cultivation tests of GECS-IGH at Toyohashi City
- 60.** Current situation of MAFF-subsidized projects for plant factories related to the disaster reconstruction (May 16, 2013)
 - Achievements in the greenhouse horticulture field and outline of Yamamoto Demonstration Research Facility in Miyagi Pref., National Agriculture and Food Organization

- Current status and issues of mobile bench cultivation in plant factory production
- Issues of controlling pests in large-scale greenhouse horticulture
- 61.** Application of LED lighting to plant cultivation (June 20, 2013)
 - Fundamental matters concerning the use of LEDs for plant cultivation
 - Influence of LED light quality on leafy vegetable growth and useful component accumulation
 - Cultivation verification using Philips' LED module
- 62.** Marketability and breeding of plant factory vegetables (July 18, 2013)
 - Trends in development by vegetable seed companies/cultivars in the Netherlands—Focusing on cases at Rijk Zwaan Co.
 - Prospects of plant factory vegetables for processing and restaurant industries
 - Trends in lettuce and tomato varieties for retailers
- 63.** Report on the development of integrated environmental control system in the 2012 fiscal year (Aug. 22, 2013)
 - Core system
 - Control method of integrated environmental control system
 - Management of nutrient solution
 - CO₂ intelligent controller
 - Intelligent controller for air temperature and vapor pressure deficit using fine fog generation
 - Visualization of CO₂ distribution data, air temperature, and vapor pressure deficit data
- 64.** Opinions offered concerning standard specifications by the Super Hort Project Association and results of questionnaire on plant factories in Japan and Korea (Sept. 17, 2013)
 - Recommendation of the standard specifications for plant factories summarized by the Super Hort Project Council
 - Production and management model of GECS (tomato)
 - Standard specifications for PFALs
 - Questionnaire results from plant factories in Japan
- 65.** Energy-saving effect and good use of multifunction agricultural heat pumps (Oct. 22, 2013)
 - Efficient use of heat pumps in greenhouse horticulture
 - Application method and examples of agricultural heat pumps
 - Good use of agricultural heat pumps
 - Good examples of heat pump utilization in agricultural facilities
- 66.** Examples of new entrants to the plant factory business (Nov. 19, 2013)
 - Current status and future prospects of the low-potassium vegetable business
 - Expanded polystyrene agricultural dome and Hokko-type cultivation system
 - Construction industry and plant factories
- 67.** Measurement and controllers in GECS (Dec. 17, 2013)
 - Development background and features of Profinder, an environment measuring equipment used in cultivation facilities
 - Pro Farm to create the future of agriculture—Marketing and concept
 - Development of air temperature/vapor pressure deficit intelligent controller—Active-sensing Networks and Tel-existence System (ANTS) by fine fog generation

- 68.** In-town plant factories (Jan. 21, 2014)
 - In-town plant factories tackled by Chiba University Plant Environmental Designing Program
 - Case study of in-town plant factory design for consumers
 - Practice examples and issues of plant factory networks
 - Experiences and possibilities of plant factory networks
 - Practice examples and possibilities of in-town plant factories
- 69.** Business management in plant factories (Feb. 18, 2014)
 - Challenge of greenhouse horticulture—My Tomato Business
 - Wagoen Cooperative's move toward direct-to-consumer (sixth industrialization)
 - Management issues and marketing strategies of plant factories
- 70.** Evaporative cooling system (Mar. 18, 2014)
 - Principle of fine fog cooling system, concept and practical application of fine fog cooling method using variable fog generation speed
 - Introduction of fine fog cooling system using variable fog generation speed in tomato cultivation facility and its effect
 - Development and application of high-performance fine fog generating nozzle
- 71.** Development of integrated environment control system (July 8, 2014)
 - Current status and issues of integrated environmental control
 - Development of integrated environment control system jointly conducted in 2012 by Japan Plant Factory Association and Chiba University
- 72.** Medicinal herbs (Apr. 23, 2014)
 - "The trend of the times has changed"—Future direction toward the industrialization of herbs and functional plants
 - Market needs of medicinal crops and efforts of Shin Nippon Pharmaceutical Co.
 - Recent activities in medicinal plant research at the Center for Environment, Health and Field Sciences, Chiba University
- 73.** Establishment of hydroponics for cucumbers (May 28, 2014)
 - What is a cucumber? Cultivation technology based on the physiology and biological features of cucumbers.
 - Cucumber hydroponic culture technique by aeroponics
 - Possibility of high-yield cucumber production by hydroponic culture
- 74.** Null-balance CO₂ enrichment (June 25, 2014)
 - Why is null-balance CO₂ enrichment important?
 - Commercialization and application of null-balance CO₂ enrichment controller
 - Equipment that creates a cultivation environment—Current status of CO₂ concentration management at production sites
- 75.** Plant factories outside of Japan (July 22, 2014)
 - Status and perspectives of PFALs in Taiwan
 - Status and perspectives of greenhouse horticulture in Israel
- 76.** Current status of plant factory consulting business in Europe and its prospects in Japan (Aug. 27, 2014)
 - Current status of consulting in Europe and activities of Green Q.B.V. Co.
 - Potential agricultural changes in Japan by consulting
 - Examples of consulting cases and prospects for consulting in Japan

77. Plant factory symposium: Direction toward attaining a “platinum society” (wealthy and aging society), method for community revolution based on plant factories, PFALs, and GECS in Kashiwanoha (Sept. 13, 2014)
 - Keynote speech “Direction to take toward the realization of a platinum society”
 - Theme lecture “Path to the revolution of local society centered on a plant factory”
 - Subcommittee Session A: GECS discussion Session B: PFAL discussion
 - Field tour
78. Cultivation of paprika and bell peppers in GECS (Oct. 22, 2014)
 - Basis and key points of paprika cultivation
 - Trends in paprika cultivation and variety development in the Netherlands
 - Current status and issues of paprika cultivation in large greenhouses in Japan
79. Hydroponics around the world (Nov. 26, 2014)
 - Environment in greenhouse cultivation: importance of vapor pressure deficit
 - North American Vertical Farm, Trends and possibilities of a vertical farm/PFAL business in the US
80. National projects that are accelerating the promotion of next-generation greenhouse horticulture (Nov. 6, 2014)
 - Nationwide deployment of next-generation greenhouse horticulture
 - Approaches of the Fuji Koyama Consortium to promote next-generation greenhouse horticulture
 - Approaches of the project to support the acceleration of next-generation greenhouse horticulture in Miyazaki Prefecture
81. Urgent need for human resource development for plant factories (Dec. 24, 2014)
 - Outline of training programs and human resource development at the plant factories supported by MAFF
 - Identification and improvement of issues at GECS sites
 - Necessity of establishing permanent human resource development centers with large-scale production facilities, learned from the Netherlands
82. Improvement of PFAL cost performance based on marketing strategy (Jan. 28, 2015)
 - Examples of PFAL business balance and management methods
 - Outline for reducing PFAL production costs, and examples
 - Business strategy of Vegetable Factory, a low-cost-vegetable plant factory
83. Current state and trend of PFALs outside of Japan (Feb. 25, 2015)
 - Deployment of PFALs overseas
 - Current state and trend of PFALs in the US
 - Movement of plant factory research and development in China
84. Concept of nutrient solution management in PFALs (Mar. 25, 2015)
 - Concept of nutrition solution management in PFALs
 - Practices of nutrition solution management in PFALs (exercise)
 - Causes and countermeasures of various physiological disorders including tipburn
 - Production of functional vegetables by special nutrition solution management

85. Issues and possibilities of low-shelf/high-density tomato cultivation system (April 28, 2015)
 - Characteristics and issues of low-shelf/high-density/three to four trusses cultivation using D-trays
 - One to two trusses cultivation system for tomato production using Nae-Terrace
 - Current status and business prospects of tomato production with high-sugar content
 - Characteristics and possibilities of tomato cultivars for low-shelf/high-density cultivation
86. Recent topics on PFALs (May 14, 2015)
 - Recent trends in PFALs outside of Japan
 - Current status and future of LED light sources for plant factories
87. Method and practicality of controlling vapor pressure deficit (June 24, 2015)
 - Importance of controlling vapor pressure deficit and application method
 - Effect of controlling vapor pressure deficit in tomato cultivation
 - Actual cases of controlling vapor pressure deficit in leafy vegetable cultivation
88. Latest movement in raising seedling technology (July 22, 2015)
 - Current status and issues of seedling production—Environment control related to seedling production
 - Technology to control intumescence on tomato seedlings
 - Latest information on grafting robots
89. Efficient use and multipurpose use of heat pumps for horticultural facilities—Aiming at reduction of utility expenses in greenhouse horticulture (Aug. 26, 2015)
 - Basics of multipurpose use
 - Proposed challenges for efficient utilization of heat pumps based on recent achievements of JPFA's work
 - Mechanism and function of heat pumps
 - Shortened depreciation period by multipurpose use
 - Effectiveness of night cooling/dehumidification by heat pumps
90. Learning from the basics: characteristics and control of pests (Sept. 30, 2015)
 - Conditions of occurrence and infection of plant diseases
 - Occurrence of insects and environment-friendly control method
91. Functional vegetables and quality labeling (Oct. 28, 2015)
 - Outline of Food Functionality Labeling Act, and issues and countermeasures for agricultural products
 - Functional components effective for prevention of metabolic syndrome and osteoporosis
 - Technique for controlling functional ingredients of vegetables by LED, etc.
92. Current development state of integrated environmental control system—How to achieve a tomato yield of 500 tons/ha! (Nov. 25, 2015)
 - Measurement of greenhouse environment and control
 - Efforts of Pro Farm to create the future of agriculture
 - From the integrated environmental control system to the advanced integrated environmental control system—Measuring the net photosynthesis rate in one greenhouse
93. Present situation and improvement of GECS production site—Increased profitability by improving untouched areas (Dec. 25, 2015)
 - Notable points on cultivation at large production facilities and methods of improvement
 - Current situation and future movement of Kochi—A new greenhouse horticulture system
 - Tomato cultivation at JA Toyohashi

94. Characteristics of LED lamps for plant factories (Jan. 28, 2016)
 - Introduction to characteristics of LED light sources
 - Showa Denko LED light source for plants
 - Japan Advance Agri LED light source for plants
 - Stanley Electric LED light source for plants
 - Ushio Lighting LED light source for plants
 - Phillips LED light source for plants
 - Toshiba LED light source for plants
 - Kyocera LED light source for plants
95. Sales, distribution, and distribution issues to be tackled for plant factory business management (Feb. 24, 2016)
 - Keynote lecture “Vegetable marketing circumstances related to plant factory business”
 - Distribution strategy for plant factory vegetables
 - Marketing and sales strategy for PFAL vegetables
96. Next-generation strawberry production system and varieties (Mar. 16, 2016)
 - Issues on strawberry production in PFALs
 - Development and deployment of “Yotsuboshi,” a jointly bred seed-propagated strawberry cultivar
 - Current status and issues of commercial strawberry production in PFALs
97. Current situation and issues of nationwide promotion project—Next-generation greenhouse horticulture and plant factories at 10 locations (April 13, 2016)
 - Current situation of a nationwide project for promoting next-generation greenhouse horticulture and plant factories, and a Japan Greenhouse Horticulture Association project
 - Technical problems and improvements observed at each site
 - Mitigation of facility management issues and operation administration issues that increase in number with the expansion of facilities—Focusing on Miyazaki as an example
98. Existing nutrient solution controllers and the status of developing a new controller (May 18, 2016)
 - Ideal recipe for nutrient solution and controller—new theory of nutrition solution management
 - Absorption behavior of nutrient and water in PFALs and efforts to develop a new method to control ingredients in nutrient solution
 - Nutrient measurement by ion electrode method—Ion measurement by compact water quality meter LAQUAtwin
 - Status of placing nutrition solution controllers and issues in PFALs—Sem Corporation’s approach
99. Recent technical progress of PFALs (June 8, 2016)
 - Recent topics related to PFALs
 - Lighting design method using LEDs, and its results
 - Environmental control in PFALs based on rate variables, and its actual performance
100. Our thoughts on 21st-century plant factories (July 13, 2016)
 - My image of the plant factory in 2025 and 2050—Toyoki Kozai
 - Near-future greenhouse horticulture aimed for by the Japan Greenhouse Horticulture Association—Yutaka Shinohara
 - Ideal status of the plant factory industry in the Olympics year (2020)—Toru Maruo

101. Improvement of working efficiency at PFALs (Sept. 7, 2016)
 - Purpose and activities of the Working Efficiency Improvement Committee
 - Business plans and the role of working efficiency improvement
 - Example of improved working efficiency in PFALs—Part 1
 - Example of improved working efficiency in PFALs—Part 2
102. Recent efforts of Chiba University GECS Consortia (1) (Oct. 2, 2016)
 - Efforts of JA Zen-Noh Tomato Land
 - Development of our agricultural business in Sumitomo Denko
 - Environmental control technology in GECS using a dry fog system
103. Recent efforts of Chiba University GECS Consortia (2) (Nov. 9, 2016)
 - Recent efforts of Daisen GECS
 - Recent efforts of Iwatani Agri Green GECS—Increase in tomato production and reduction of production costs
 - Recent efforts of Mitsubishi Plastic Agri-Dream GECS—Aiming to establish high-yield production technology for high-sugar-content tomatoes
104. Latest trend of greenhouse horticulture in the US, the Netherlands, and Korea (Dec. 13, 2016)
 - Greenhouse horticulture in the US
 - Researchers' reports on tours in the Netherlands
 - Greenhouse horticulture in Korea
105. Latest trend of PFALs in the Netherlands, the US, and China (Jan. 11, 2017)
 - Noteworthy latest trend of the PFAL market in the Netherlands and the US
 - Latest trend of PFALs in China
 - Possibility of breeding exclusive varieties for PFALs and breeding utilizing PFALs
106. Preparations for constructing larger GECS and PFALs—Present state of regulations and direction of relaxation (Feb. 8, 2017)
 - Conditions surrounding various regulations to keep in mind when developing plant factories
 - Effective utilization of abandoned cultivation land—Initiatives to encourage greenhouse horticulture, integrate agricultural land, train leaders, and expand employment
 - Experiences of various procedures necessary for construction and government approval of PFALs
107. Japanese Type Innovative Greenhouse Horticulture/Plant Factory Industry Network (Mar. 8, 2017)
 - Outline of “Japanese Type Innovative Greenhouse Horticulture/Plant Factory Industry Network” and related plans
 - Outline of “Low-Cost Greenhouse Horticultural Research Network” and future plans
 - Projects working in cooperation with the “Japanese Type Innovative Greenhouse Horticulture/Plant Factory Industry Network”
 - Establishment of shipping adjustment storage process by harvesting immature tomato fruits
 - Development of tomato production prediction system utilizing sensor network

- Development of advanced integrated environmental control system that includes a function to control the net photosynthetic rate to increase the tomato yield and reduce production costs
 - Industrial innovation network business
108. Characteristics of LEDs and light environment in the cultivation area (April 12, 2017)
 - Physical quantities of plant light environment and performance factors of LED light on plants
 - Measuring the characteristics of LED lamps and luminaires and its application for controlling the light environment of plants
 - Influence of various factors on the light environment in the PFAL cultivation area
 109. Tokyo Olympics and Paralympic Games and trend toward securing vegetable safety (May 10, 2017)
 - Procurement of foods and promotion of GAP for the Tokyo Olympics and Paralympic Games
 - Agricultural production required in the global age and GAP—Olympic Food Procurement Standards
 - Actual situation of safety and hygiene management in PFALs, and its issues
 110. Possible utilization of micro/nanobubble technology for plant factories (June 14, 2017)
 - Sterilization using micro/nanobubbles
 - Possibility of utilizing micro/nanobubble technology for hydroponic cultivation
 - Application of fine bubbles to leafy vegetables in plant factories
 111. New technology and topics on seeds and seedlings required in plant factories (July 19, 2017)
 - Possibility of varieties for hydroponic cultivation from the view of seed companies
 - Seed quality required by the seedling production industry and the current status of seedling production
 - Seed coating and its related technologies
 - Comprehensive discussion
 112. Productivity and its improvement in PFALs (Sept. 13, 2017)
 - Definition of productivity and its improvement
 - Concept of productivity barometer and its correlation with business performance
 - Case studies of improved productivity and factor analysis
 - Comprehensive discussion
 113. Cost and performance of hydroponic cultivation systems (Oct. 11, 2017)
 - Outline of Iwate Ginga Farm, characteristics and issues of tomato cultivation in GECS
 - Outline of agricultural business of Orix Co., characteristics and issues of hydroponic cultivation (especially leafy vegetables) systems
 - Outline of studies on low-cost model greenhouses, costs, performance, and issues of hydroponic cultivation systems
 114. Diseases currently posing a problem in GECS and PFALs, and their control (Nov. 14, 2017)
 - Diseases and their control in greenhouse horticulture
 - Diseases occurring in hydroponic cultivation, and their countermeasures
 - Improved NFT system for leafy vegetables, control of diseases of spinach in the Napperland system

115. Startup guide for larger GECSs and PFALs to improve the process (Dec. 13, 2017)
 - Why is a manual required?
 - Guide for improved startup of GECSs and PFALs—Each chapter includes a Construction section, Operation section, and Standardization section
116. Recent topics on LEDs in PFALs (Jan. 10, 2018)
 - Production of high-added-value plants in PFALs—Focusing on the production of pharmaceutical raw materials
 - Effect of white LEDs on optimizing the photosynthesis environment of PFALs, and its application
 - LED lighting technology for plant growth promotion and morphological control
117. How will AI change plant factory technology? (Feb. 7, 2018)
 - How AI will change plant factories
 - Lead research on plant phenomics using AI technology and its applications
118. Development status of nutrient solution controller (Mar. 14, 2018)
 - Concept and goal of developing a nutrient solution controller
 - Can we visualize in real time the ion composition of nutrient solution that changes during cultivation?
 - EC and pH are determined by the activity (amount) of each ion constituting the nutrient solution

28.3 Business forums

JPFA and Chiba University have jointly conducted annual business forums on GECS and PFALs since 2010. Based on the questionnaire responses obtained from participants at the end of each forum, critical issues at the production sites at that time, and the development status of countermeasures against the issues, the forum committee reviews and reorganizes the composition and contents of the training programs every year.

1. Overview of business forums in the 2017 fiscal year (April to March)

In the 2017 fiscal year, 14 business forums on GECS and PFALs were offered as described below.

Title	Format	Period	Length
Basic course on PFALs	Lectures, practice, seminars	June 6–9, 2017	4 days
Management of nutrition solution	Lectures, practice, seminars	June 21–23, 2017	3 days
Development of optimum nutrition solution management for your production site	JPFA analysis and evaluation of 45–60 samples of nutrition solution from each participant's site. Lectures and seminars were held to develop the nutrition solution management system for each site	July 4, 2017 Sept. 8 Nov. 7	4 months
Production management	Lectures, seminars	July 24–28, 2017	5 days
	Practice Practice	Aug. 14–18, 2017	8 months

Long-term training for production managers on GECS	Practice Practice Seminars Practice	Oct. 16–20 Dec. 11–15 Jan. 3–5, 8, 9 Feb. 13 Mar. 5, 6	
Basic course on GECS	Lectures, practice, seminars	Aug. 7–10, 2017	4 days
Dynamics of photosynthetic products and environmental control based on this	Lectures	Sept. 5, 6, 2017	2 days
Advanced course on GECS	Lectures, practice, seminars	Sept. 20–22, 2017 Oct. 18–20 Nov. 15–17	9 days
Plant factory management	Seminars	Oct. 24–26, 2017	3 days
PFAL business plan	Lectures, seminars	Dec. 6, 7, 2017	2 days
Cultivation environment and plant reaction	Lectures, seminars	Dec. 20, 2017	1 day
Advanced course on PFALs	Practice, seminars	Jan. 17–19, 2018 Feb. 21–23, 2018	6 days
Assembly of environmental monitors	Practice	Jan. 30, 2018	Half day
Growth control by environmental control	Lectures, seminars	Feb. 20, 2018	1 day

2. In this session that focuses on PFALs, two business forums were held: a basic course on PFALs and an advanced course on PFALs. All courses were conducted in Japanese, but some English courses started in October 2018.

28.3.1 Basic course on PFALs

The basic course is for people who plan to learn about or start a PFAL or have just started a PFAL. Participants will gain an understanding of the theory of PFALs, plus basic knowledge on PFAL cultivation, environment control, facilities, and keys for business success.

- Current situation and issues of PFALs (lecture)
 - Vertical agriculture in the world
 - Current cultivation systems and protocols, and issues to be improved (lecture)
- Plant physiology on photosynthesis (lecture)
 - Basis of photosynthesis
 - Photosynthesis responding to environments

- Production improvement
- Reduction of lighting cost by light sources and reflection boards (lecture)
 - Comparison between fluorescent and LED lights
 - Improvement of light utility by using reflection boards
 - Improvement of light utility by improved light distribution
- Reduction of air conditioning cost (lecture)
 - Ventilation rate and necessity of measuring heat transmission
- Plant nutrition related to absorption of nutrition and water (lecture)
 - Absorption of nutrition and water, and transpiration
 - Functions of water and nutrition
 - Physiological disorders and avoidance measures
- Cultivation management—seeding to harvesting (practice)
 - Seeding, nursing, transplanting
 - Plant management
 - Harvesting, postharvest processing, precooling
- Basis of hydroponics (lecture)
 - Basis of nutrient solution composition and management
- Factory structure and equipment (lecture)
 - Factory structure
 - Placement of cultivation benches
 - Basic design
 - Devices for environment control
- PFAL business
 - For sustainable business
 - LED power-saving type vertical agriculture
 - Reduction of running costs
 - Creation of business model
 - Road to sustainable management

28.3.2 Advanced course on PFALs

The advanced course is for people who are already engaged in PFAL production and want to level up their understanding and skills to make their business sustainable and profitable. Participants will acquire a deeper understanding of PFAL facilities, LED utilization, and control systems, and master the required cultivation skills.

- Factory design and equipment (lecture)
 - Insulated and closed cultivation room
 - Air conditioners and fans
 - Hydroponic system
 - CO₂ supply system
 - Measurement/control system
 - Building design
 - Airtightness (ventilation rate) and its measurement

- Distribution of light strength, light utilization factor
 - COP of air conditioners
- How to create a production system (practice)
 - Materials for cultivation system
 - Assembling the frame
 - Assembling the cultivation beds
 - Pump system for nutrient solution
 - Installing the lighting system
 - Installing controllers
 - Trial run
- How to measure the thermal reflux factor and ventilation frequency, and how to utilize the obtained data (practice)
- Tours to actual commercial and research facilities
- Cultivation (practice from seeding to germination)
 - Characteristics of seeds
 - Technique for better germination rate
 - Management after seeding
- Cultivation (practice from transplanting to harvesting)
 - Transplanting
 - Management after transplanting
 - Harvesting and postharvest processing
- Evaluation of crops (practice)
 - Concentration of nitric ion
 - Ascorbic acid (vitamin C), etc.
- Management of nutrient solution (lecture)
 - Basis of nutrient solution
 - Issues caused by nutrient solution
 - Managing the concentration and volume
- Analysis of nutrition solution and how to utilize the obtained data (seminar)
 - Necessary data for managing the nutrition solution
 - Method for utilizing the data
 - Advice based on the actual analysis data
- Basis of physical disorders
 - What are physiological disorders?
 - Physiological disorders other than tipburn, and their causes
- Cultivation management and tipburn
 - Cultivation management
 - Tipburn and environmental factors
 - Tipburn and nutrient solution
- Quality management to secure safety
 - Japan and global GLP
 - Key points for hygiene management
 - Nutritional value of products

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PART

PFALs in operation
and its perspectives

4

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Selected PFALs in the United States, the Netherlands, and China

29

29.1 Introduction

An increasing number of people in the fields of research, system development, business, investment, etc. have started to be involved in plant factories with artificial lighting (PFALs) in multiple regions of the world since 2010 (Kozai, 2016). It should be noted that the diversification and internationalization of the PFAL movement has been accelerating since 2015. Among many countries, a notable growth or potential development can be seen, for instance, in the United States, China, and the Netherlands. The overview and outlook of PFALs and R&D are described in Chapter 3 (Asia and North America) and Chapter 4 (Europe). In this chapter, selected PFALs in the United States, the Netherlands, and China, including AeroFarms, GrowWise Center (Signify), BrightBox, and Sanan Sino-Science are introduced. Two of the PFAL facilities in the Netherlands, GrowWise Center and BrightBox, are rather focused on research-oriented business. In the Netherlands, it is well known that Wageningen University & Research (WUR) is actively involved in research in this sector. Occasionally, terms other than PFAL, including vertical farm, city farm, etc., are used in this chapter.

29.2 AeroFarms in the United States

Ed Harwood

AeroFarms, Newark, New Jersey, United States

29.2.1 Company outline and vision and mission

A certified B corporation, AeroFarms¹ aims to transform agriculture by building and operating environmentally responsible farms throughout the world to enable local production at scale and nourish communities with safe, nutritious, and delicious food. Since 2004, AeroFarms has been leading the way with proprietary technology to address the global food crisis by building, owning, and operating indoor vertical farms that grow in a sustainable and socially responsible way, setting a higher standard for totally protected agriculture from seed to package. Their passion is great-tasting food and sharing the harvest within communities. Above all, they are committed to leading by example, helping

¹<https://aerofarms.com/>.

inspire and foster a collaborative and caring culture, and ultimately making a positive impact on the world.

29.2.2 Technical characteristics of the company

AeroFarms does not use soil or sun. Plants are grown on AeroCloth, a patented cloth substrate that is reusable and made from recyclable BPA-free water bottles. Instead of the sun, they have developed proprietary LED arrays to deliver the optimal spectrum, intensity, and frequency for each plant variety and each stage of growth. The company uses aeroponics to mist the roots, using up to 95% less water than field farming, and does not use any pesticides. AeroFarms' growing beds are stacked on top of one another in indoor controlled growing warehouses, generating up to 390 times more productivity per square meter annually compared with field farming. For leafy greens, they harvest up to 30 times per year, and for microgreens over 70 harvests per year. For each harvest, the company tracks the entire growing process from seed to package, and captures abiotic data and utilizes machine vision and learning to enable a thorough study of the crop.

29.2.3 Business features and business model

AeroFarms builds, owns, and operates its own indoor vertical farms, leveraging 15 years of experience (Fig. 29.1). They employ over 20 engineers and scientists whose understanding of plant biology, growing systems, and environmental controls allows continuous testing and improvements. The core economics of the business are based on margins generated on the produce they sell, factoring in their low-cost operating model and customer demand. As they expand around the world, they look to strategic partners and joint ventures to further develop farms. The company is as much a technology company as a farmer, aiming to extend beyond food into the pharmaceutical, cosmeceutical, and nutraceutical industries as well. Key to its business model is hiring locally both skilled and unskilled labor, not owning land and facilities, and a strong connection to local culture.



FIGURE 29.1

Plants grown in multitier racks as viewed from above.

29.2.4 Main crops and product brand name

Over 400 different baby leafy greens, microgreens, and herbs have been tested. Among them, eight combinations are offered at retail including, arugula, kale, pak choi, watercress, red romaine, and ruby streaks mustard. “Dream Greens” is their retail brand, and “AeroFarms” brand is used for foodservice and wholesale (Fig. 29.2).

29.2.5 Outline of PFAL of AeroFarms

Outline of the 9th AeroFarms is shown in Table 29.1 and Figs. 29.3–29.5.

29.2.6 Challenges

The endeavor is a very complex undertaking, requiring deep expertise in horticulture, engineering, construction, data systems, food safety, nutrition, and sales and marketing. To grow plants indoors, a symbiotic relationship exists between the plants and the company’s growing system. The company is harnessing large and more datasets to standardize the biology underlying the crop production and deliver a higher quality product with better nutrition and flavor. They seek to build on a team of 120 employees including researchers, engineers, etc. by recruiting from experts outside agriculture to leverage the best practices and deliver new insights in farming. They are striving to write the new



FIGURE 29.2

Product package with retail brand.

Table 29.1 Outline of PFAL of AeroFarms.		
Plant factory name	9th AeroFarms	
Location	Newark, New Jersey, United States	
Month/Year of initial sales ^a	September 2016	
Land area	14,000 m ² (3.5 acres)	
Floor area of PFAL building	6503 m ² (70,000 f ²)	
Daily production capacity	2500 kg of baby leafy greens	
Cultivation room	Floor area	3716 m ² (40,000 f ²)
	Ceiling height	11 m (36 f)
	No. of tiers ^b	12 tiers
	Cultivation beds	Aeroponics
	Light source	LEDs (proprietary LED array design and source)
Substrate (supports)	Cloth substrate (“AeroCloth”)	
Produce without roots	Yes	
Automation	Automated: Sowing, harvesting, packing (transplanting is not required)	
^a Initial sales includes trial sales.		
^b Tiers are also referred to as “layers.”		



FIGURE 29.3
Interior view of a cultivation room of 9th AeroFarms.

playbook for agriculture and are also working with universities and schools to develop the next generation of farm workers who are skilled and prepared for indoor vertical farming. For food safety, the company can track the entire process from seed to package, helping take traceability to a new level, and more importantly, helping set a new standard for the industry overall.

**FIGURE 29.4**

Plants with roots from a lateral view.

**FIGURE 29.5**

Schematic of a cultivation system.

29.2.7 Research and development

Core research and development is improving the current technology by automating, expanding our understanding of the phytochemistry of plants, and driving plant phenotypic plasticity for the best-in-class crops. In addition to growing and selling leafy greens, the company works on major innovations in plant science and technology and is improving systems to lower the cost of goods and capital investments for future farms.

In 2018, AeroFarms began collecting data on a transformational project with the Foundation for Food & Agriculture Research (FFAR), a nonprofit organization established through bipartisan congressional support in the US 2014 Farm Bill, on a public-private research partnership to understand

the connection between phytochemistry, abiotic impacts, and sensory evaluation for organoleptic properties. In addition, in 2018, they partnered with major technology companies, such as Dell, on projects including machine learning and internet of things (IoT) integration, bringing agriculture into the future at a rapid pace.

29.2.8 Future plans

There has never been a greater need for safe, dependable, nutritious food, and the company is scaling quickly to build more responsible farms in major cities all over the world. New paradigms that factor in all the stakeholders including the environment and our communities are needed. The focus is not just on indoor vertical farming, but also on how to help transform agriculture overall. Ultimately, the firm hopes to serve as an inspiration and catalyst to foster even greater innovation for generations to come.

29.3 Signify facility in the Netherlands—GrowWise center

Eri Hayashi

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29.3.1 Company outline, vision, and mission

The lighting company Signify² (formerly Philips Lighting) has been focusing on LED solution business for horticulture and city farming. The methodology/source for the section is shown in Table 29.2.

Along with supplemental lighting for greenhouses, they have provided LEDs to a number of PFALs internationally, including Asia and North America. With their vision toward a smarter and more sustainable way of growing vegetables for urban populations, they founded their own research facility, GrowWise Center, which opened on July 6, 2015 in the southern Netherlands. This facility is on the third floor of Building 7 at the High Tech Campus located in Eindhoven City.

29.3.2 Business features and business model

The major focus of the business of Signify is to sell Philips GreenPower LED lighting products (Fig. 29.6). They attach great importance on research on lighting and other environmental factors

Table 29.2 Methodology: Field work conducted by the author and source for the section.	
GrowWise center, Signify	Information provided by Signify via questionnaire response (October 27, 2018 and March 1, 2019), personal communications (January 15, March 8 and March 19 in 2019), during author’s visit to GrowWise center (October 20, 2016), and public data

²www.philips.com/growwise.

**FIGURE 29.6**

Philips GreenPower LEDs installed in the GrowWise Center.

(Photo courtesy of Signify).

related to PFALs. The GrowWise facility serves as a research center to accumulate and advance the lighting technologies for PFALs and to facilitate their marketing and sales, ultimately helping people through their products. Signify (through the GrowWise Center) provides customers with services such as variety screening or comparison, consultations, system architecture discussions, grower training, growth recipe development, nutritional value analysis and optimization, shelf life trials, and optimization and substrate trials. These services are often offered free of charge with the purchase of their lighting products. They believe in providing this support so that their customers can achieve optimal use of the light recipes and the highest return on their investment.

29.3.3 Technical characteristics and outline of GrowWise center

Signify believes that the quality of a PFAL depends on how well the lighting, climate control, sensors, logistics, and software control all work together. GrowWise Center is designed with an integrated system that allows Signify to optimally control the environment in order to identify the optimal set-points of the environment, which they call “growth recipes.” They aim to find and specify the ideal growing conditions for vegetables, fruits, and herbs to achieve better results, such as higher yields, enhanced flavors, and high-quality plants with increased nutrients and vitamins (Fig. 29.7).

As shown in Table 29.3 and Fig. 29.8, the facility has eight cultivation rooms with different types of LED lamps and one germination room, with a total cultivation area of 234 m² (Anpo et al., 2019). Of the eight cultivation rooms, six are equipped with a multitier cultivation system. Signify utilizes two of those rooms for research in cooperation with Signify Research, including nutrient control and quality aspects of multiple crops grown under their LEDs. In addition, there is one “high-wire” room for tomatoes, cucumbers, melons, and peppers. The facility has one room that is equipped with multitier racks for soft fruits, and this room is planned to be used for strawberries in 2019. Further details of crop varieties that have been tested are shown in Table 29.4.

**FIGURE 29.7**

Plant grown in the GrowWise Center.

(Photo courtesy of Signify).

The entire facility is controlled using the GrowWise Control System and Priva Indoor Farming Software. No natural sunlight comes into the cultivation rooms, as all the crops are grown only with LEDs. In each room, Philips GreenPower Dynamic Production Modules are installed above each cultivation rack to grow plants, and these modules are equipped with blue, red, white, and far-red LEDs.

Each cultivation rack is 1.5 m wide $\times$ 6 m long with four tiers, and the distance between each tier is 0.85 m. The distance from the bottom of the lighting module to the surface of the cultivation panel is 0.35 m. Since this research facility aims to study the dynamics of multiple environmental conditions including light and crops, the researchers at the facility apply a variety of cultivation methods including the nutrient film technique (NFT), deep flow technique (DFT), aeroponics, and drip irrigation. As for the cultivation substrate, a wide range of types have been tested, such as rockwool, peat, coco, cellulose, foam, organic substrate, and textile, as well as testing without substrate (i.e., roots are in direct contact with nutrient solution).

29.3.4 Targeted market, challenges, and future plans

As the world's PFAL industry expands, so does the target market of Signify. To date, their main target markets include Japan, China, Singapore, other emerging Asian PFAL markets, and the United States/Canada. In Europe, the main focus of growers is using LEDs in greenhouse production, as the climate conditions and infrastructure are relatively optimal in the region. According to Signify, there are already five young plant producers that use a PFAL to grow young plants and some producers that have a PFAL for growth from seed to harvest (Fig. 29.9A-B). In general, PFAL facilities that produce a crop from seed to harvest are limited. Signify explains that this is because European markets have access to an abundance of high-quality produce coming from greenhouses and are not willing to pay a premium price for the added value of PFAL-grown products.

Table 29.3 Outline of PFAL of GrowWise Center.	
Plant factory name	GrowWise center
Location	Eindhoven, the Netherlands
Month/year of initial sales ^a	July 2015
Production capacity	100 kg/m ² per year, 250 g/head
Cultivation room	234 m ² (8 cultivation rooms)
	Cultivation area
	No. of racks and tiers ^b
	Distance between tiers ^c
	Width and length of each rack
	Distance between racks (aisle width)
	Cultivation beds
	Light source
Substrate (supports)	NFT (nutrient film technique), DFT (deep flow technique), aeroponics, shallow water, drip irrigation
	LEDs (philips greenpower LED light)
	Peat, cocopeat, coco, cellulose, foam urethane, rockwool, water (no substrate, direct rooting into water), organic substrate, textile
Automation in PFALs 1 and 2 ^d	Manual: transplanting, harvesting, packing (shelf life equipment available); automated: sowing (irrigation fully automated)

^aInitial sales includes trial sales.

^bTiers are also referred to as “layers.”

^c(1) indicates vertical distance between frames of the rack, (2) indicates vertical free distance from the bottom of lights to the cultivation panel.

^dItems including land area, floor area of PFAL building, PFAL operating rate, floor area of cultivation room, ceiling height of cultivation room, and produce without roots were not answered by the company.

Source: Based on information provided by Signify via questionnaire response (October 27, 2018 and March 1, 2019), personal communications (January 15, March 8 and March 19 in 2019).

Signify aims to continue studying and generating data on lighting systems and how the lighting environment interacts with other cultivation parameters, so that they can better support their customers with diverse production goals. Moving forward, they intend to introduce greater flexibility in their lighting systems partly by applying artificial intelligent technologies, while continuing to generate more data on their controlled systems.



FIGURE 29.8
Interior view of GrowWise Center cultivation room. *(Photo courtesy of Signify).*

Table 29.4 Main crops grown for research in the GrowWise Center.	
Lettuce	Butterhead, Romaine (Cos), gem, frill (ice), iceberg
Baby leaf greens	Leaf mustard, mizuna, red beet, pak choi
Herbs	Basil, coriander, dill, rosemary, thyme, brassicaceae, mint, oregano
Microgreens	Various
Edible flowers	Viola, borage, toothache plant, mint, basil
Brassicaceae	Broccoli, bimi, kohlrabi, pak choi, cauliflower, radish, kale
Fruiting vegetables	Strawberry, melon, pepper, tomato, cucumber

29.4 BrightBox in the Netherlands

29.4.1 Company outline, vision, and mission

BrightBox Venlo³ is a commercial PFAL research center located in Venlo, the Netherlands, specializing in research, production, education, and knowledge sharing. The methodology/source for this

³<http://www.brightbox-venlo.nl/en/>.

**FIGURE 29.9**

(A) Interior view of Planet Farms cultivation room in Italy, equipped with Philips LED lights. (B) Interior view of Planet Farms in Italy, equipped with Philips LED lights.

(Photo courtesy of Signify).

section is shown in [Table 29.5](#). They aim to open the future of food crops and other plants in a closed environment to help secure global food supply in an efficient way. Their mission is to contribute to safer, more secure, more local and healthier plant production systems.

Table 29.5 Methodology: field work conducted by the author and source for the section.	
BrightBox	Information provided by BrightBox via questionnaire response (November 8, 2018 and March 5, 2019), personal communications (March 10, 2019), and public data.

29.4.2 History and technical background of the company

BrightBox was founded in 2015 and was designed and developed with the cooperation of Botany BV, Signify (formerly Philips Lighting), and HAS University for Applied Sciences. Under this structure, Botany mainly handles applied research, Signify handles lighting, and HAS University handles education. Based on their combined academic and industrial expertise, they conduct multiple research studies, including technical and practical applications for PFALs.

29.4.3 Features of the business

BrightBox conducts applied research both for their clients and for themselves to generate new knowledge and skills, often in an open innovation setting or as contract-based confidential research. This knowledge and experience are applied to academic and practical education for students and professionals in extension courses that they offer. Given their emphasis on open innovation, visitors to the facility are usually welcomed.

29.4.4 Outline of PFAL and technical characteristics

As shown in Table 29.6, there are three cultivation rooms; two for research, each with a floor area of 24 m² (total 48 m² for research) and the third is mainly for production, with a floor area of 192 m². Each room contains five-tier cultivation racks, 1.4 m wide and 7 m long (Fig. 29.10). As for cultivation methods, a DFT with a 4 cm water layer and 1 cm ebb-and-flow are applied as well. BrightBox adopts Philips (Signify) LEDs with multiple light spectra, including blue-deep red (600–700 nm), blue-deep red-far red, white-deep red, white, and deep red-far red. The rooms are also equipped with a climate control system designed by Priva. Regarding target crops for research, they mainly focus on herbs and leafy vegetables, as well as strawberries and young ornamental plants.

29.4.5 Challenges and future plans

Challenges specifically addressed include achieving higher yield, testing high-density cultivation of baby leaf products, and further attempts at soft fruit such as strawberries and Asian vegetables. Moving forward, possible future options for BrightBox include installing dynamic lights for production and creating new facilities for tall crops such as tomatoes.

Table 29.6 Outline of PFAL of BrightBox.		
Plant factory name		BrightBox
Location		Venlo, the Netherlands
Month/year of initial sales ^a		February 2015
Daily production capacity		250 g/head × 200 heads (50 kg/m ² per year)
Cultivation room	Floor area	Research room: 48 m ² (24 m ² × 2 rooms) Production room: 192 m ²
	No. of racks and tiers ^b	4 racks, 5 tiers
	Distance between tiers	0.8 m
	Width and length of each rack	Width: 1.4 m, length: 7 m
	Distance between racks (aisle width)	1 m
	Cultivation beds	DFT (deep flow technique) with 4 cm water layer and 1 cm ebb-and-flow
	Light source	LEDs (philips LEDs)
Substrate (supports)		Rockwool, cocopeat, etc.
Automation in PFALs 1 and 2 ^c		Manual: sowing, transplanting, harvesting, packing

^aInitial sales includes trial sales.
^bTiers are also referred to as “layers.”
^cItems including land area, floor area of PFAL building, PFAL operating rate, cultivation area, ceiling height of cultivation room, and produce without roots were not answered by the company.
Source: Based on information provided by BrightBox via questionnaire response (November 8, 2018 and March 5, 2019), personal communications (March 10, 2019), and public data (BrightBox, 2018. BrightBox Clear, Smart Research for Growers and Entrepreneurs. Venlo, the Netherlands, 3pp.).



FIGURE 29.10

Interior view of BrightBox cultivation room.

(Photo courtesy of BrightBox).

29.5 Fujian Sanan Sino-Science photobiotech in China

29.5.1 Company outline, vision, and mission

Fujian Sanan Sino-Science Photobiotech Co., Ltd.⁴ (Sanan Sino-Science) was cofounded in 2015 by the Institute of Botany, the Chinese Academy of Sciences (IB-CAS) and the Fujian Sanan Group (San'an) Quanzhou, Fujian, China. Combining the IB-CAS' expertise in botany and the leading LED optoelectronic technology of San'an, the company aims to apply optical biotechnologies in the areas of modern controlled-environment agriculture and biopharmaceuticals. The methodology/source for this section is shown in Table 29.7.

Sanan Sino-Science focuses on research and development. In addition to the PFAL facilities for plant production located in Anxi County, Fujian Province, a research institute composed of two research centers is located in Beijing and Fujian provinces. There are also two engineering and technical centers located in Xiamen, China and Las Vegas, the United States.

29.5.2 Business features and business model

Sanan Sino-Science is focusing on the development and sales of LEDs for plant growth, cultivation systems, and other technologies related to PFALs.

1. Direct sales of systems: They sell their own plant-growth lights and other systems relevant to PFAL technologies, such as modular cultivation systems, automated intelligent production systems, and turnkey solutions for PFALs.
2. PFAL operation and sales of plants: They operate PFALs to grow plants, including leafy vegetables and medicinal plants (*Anoectochilus*, *Dendrobium huoshanense*, etc.) as shown in Figs. 29.11 and 29.12.
3. Research and development: Using their research infrastructure, they focus on the demonstration and application of optical biotechnologies. They also provide clients with technical support for industrialization.
- 4 Cooperative investment for PFAL development: They announced a joint investment plan with a Singaporean company to initiate a large-scale PFAL operation in Singapore (Sanan Sino-Science, 2018). Sanan Sino-Science aims to expand their business activities through the provision of PFAL technology and turnkey systems internationally.

Table 29.7 Methodology: Field work conducted by the author and source for the section.

Fujian Sanan Sino-Science photobiotech	Information provided by Sanan Sino-Science via questionnaire response (September 6, 2018, March 22, 2019), personal communications (August 13, 2018, November 14, 2018, March 22, 2019), author's visits to their PFALs (January 20–22 in 2017), and lecture material, "research and industrialization on PFAL of Sanan Sino-Science (in Japanese)" at the 125th workshop at Japan plant Factory Association on November 14, 2018

⁴<http://www.sananbio.com>.

**FIGURE 29.11**

Product package with retail brand of Sanan Sino-Science.

(Photo courtesy of Sanan Sino-Science).

**FIGURE 29.12**

Package of medicinal plants of Sanan Sino-Science.

(Photo courtesy of Sanan Sino-Science).

29.5.3 Outline of PFALs of Sanan Sino-Science

As shown in Table 29.8, Sanan Sino-Science operates three PFAL facilities: in Anxi and Jinzhai in China, and in Las Vegas in the United States. The facilities are equipped with self-developed cultivation modules and LEDs (Fig. 29.13). In their three-story facility for vegetable production in Anxi, Fujian Province, the total floor area of all the cultivation rooms combined is 10,000 m² and a nutrient film technique (NFT) system is used as the cultivation method. Their standard cultivation module consists of six-tier racks supplied with nutrient solution and LEDs, and the water piping and electrical connections are unified within the racks. Each tier of the cultivation racks is equipped with multiple LEDs with different spectra based on the plant variety and cultivation stage. Sanan Sino-Science has

Table 29.8 Outline of PFALs of Sanan Sino-science.

Plant factory name	PFAL1: Fujian Sanan Sino-Science Photobiotech co., Ltd., PFAL2: Anhui Sanan Biological co., Ltd., PFAL3: Sino-Science North America Photobiotech Inc.	
Location	PFAL1: Anxi, Fujian, China PFAL2: Jinzhai, Anhui, China PFAL3: Las Vegas, Nevada, United States	
Month/year of initial sales ^a	PFAL1: August 2016, PFAL2: June 2018 PFAL3: July 2018	
Daily production capacity	PFALs 1, 2, and 3: 1800 kg in 10,000 m ² of leafy vegetables	
Cultivation room	Floor area ^b	PFAL1: (1) vegetable production (no automation): 7500m ² (2500 m ² × 3 stories), (2) automated PFAL: 1200 m ² , (3) medicinal plant production: 20,000 m ² ; PFAL2: (1) vegetable production: 3500 m ² , (2) medicinal plant production: 7500 m ² ; PFAL3: Vegetable production 5000 m ²
	Cultivation area	PFAL1: (1) vegetable production (no automation): 10,000m ² , (2) automated PFAL: 1300m ² , (3) medicinal plant production: 26,000 m ² ; PFAL2: (1) vegetable production: 5000 m ² , (2) medicinal plant production: 15,000 m ² ; PFAL3: Vegetable production 7000 m ²
	Distance between tiers ^c	PFALs 1, 2, and 3: 0.20–0.28 m or diverse distance depending on plant height
	Cultivation beds	PFALs 1, 2, and 3: NFT (nutrient film technique)
	Light source	PFALs 1, 2, and 3: LEDs (self-developed light spectrum and LED lamps)
Substrate (supports)	PFALs 1, 2, and 3: not used for vegetable production.	
Produce without roots	Yes	
Automation in PFAL 1 [(2) automated PFAL] ^d	Automated: sowing, transplanting, harvesting, packing	

^aInitial sales includes trial sales.

^bFloor area of cultivation rooms of PFALs 1, 2, and 3 includes area for cleaning panels, sowing, seedling production, transplanting, harvesting, packing, etc.

^cTiers are also referred to as “layers.”

^dItems including, land area, floor area of PFAL building, PFAL operating rate, ceiling height of cultivation room, no. of racks and tiers (layers), width and length of each rack, and distance between racks (aisle width) of cultivation room were not answered by the company.

Source: Based on information provided by Sanan Sino-science via questionnaire response (September 6, 2018, March 22, 2019), personal communications (August 13, 2018, November 14, 2018, March 22, 2019), author’s visits to their PFALs (January 20–22 in 2017), and lecture material, “Research and Industrialization on PFAL of Sanan Sino-Science (in Japanese)” at the 125th workshop at Japan Plant Factory Association on November 14, 2018.



FIGURE 29.13

Interior view of cultivation room of Sanan Sino-Science.

(Photo courtesy of Sanan Sino-Science).

been developing new cultivation models, including their Automated Intelligent Production System at the Jinzhai City facility, in hopes of reducing labor costs.

The main crops grown in their facilities include lettuce, pak choi, *Solanum* vegetables, ice plants, baby leaf greens, fruits, medicinal plants (*Anoectochilus roxburghii*, *Dendrobium sp.*), and plant tissue culture. Their produce is shipped to supermarkets and restaurants in China. The wholesale price of their products (e.g., leafy lettuce) is estimated to be 30–35 RMB/kg and the retail price 60–70 RMB/kg as of 2018.

29.5.4 Technical characteristics and research and development

Sanan Sino-Science strives to integrate scientific research and industrialization. Among its approximately 400 employees are an estimated 168 researchers, including 13 with PhDs specializing in photology, biology, pharmacology, industrial design, etc. To date, they have developed an in-house modular integrated cultivation system, an automated intelligent production system, LEDs for plant growth, and other related technologies.

According to Sanan Sino-Science, they have developed more than 80 tailor-made light spectra for regulating photosynthesis, morphogenesis, growth productivity, second metabolites, etc. Among those spectra, 43 are used for commercial production and research for a variety of plants, including lettuce, pak choi, *Solanum* vegetables, ice plants, baby leaf greens, fruits, medicinal plants (*Anoectochilus roxburghii*, *Dendrobium sp.*), and plant tissue culture. Nutrient solutions for each of these plants are also developed in-house.

While developing their original cultivation systems, their upcoming latest model is expected to increase production by nearly 25% and save about 17% in energy consumption compared with the existing model. The electricity efficiency is anticipated to be 8 kWh/kg for growing frill lettuce with their system as of 2018.

29.5.5 Future plans

Sanan Sino-Science aims to develop LEDs with special spectra for a wider range of plants. As they hope to cover a greater variety of PFAL-grown crops, their major interest would be fruits, particularly strawberries, and Chinese medicinal plants. By applying the highly efficient LED chip and packaging technology of the San'an Group, they intend to develop more lamps with different types of spectra to grow different plants.

Furthermore, they aim to develop innovative PFAL technologies, such as a highly automated cultivation system to achieve fully automated plant production and higher resource use efficiency including lower electricity consumption and labor costs. They also intend to develop a self-sustaining shipping container PFAL with self-supplied power, suited for severe cold regions, for instance. Additionally, they plan to improve their culture technology to increase the quality and efficiency of plant production. Along with fresh produce, innovative biological medicine derived from natural plant compounds could be a target area also.

Chinese consumers have become keen on the safety of agricultural products in recent years and Sanan Sino-Science believes that the highly efficient and sustainable plant production method of PFALs is an important way to meet the strategic needs of the country. They therefore aim to expand their investments upstream and downstream of the industry chain. They are also interested in actively expanding to foreign markets and exporting their developed equipment and technical service.

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Selected PFALs in Japan

30

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30.1 Introduction

Plant factories with artificial lighting (PFALs) are attracting attention globally. Despite differences in background or motivation for operating a PFAL for each organization or individual, it is worth noting the dynamics of opportunities and possibilities for PFALs that have emerged in recent years. In fact, particularly since 2015, an increasing number of people with diverse backgrounds have become involved in the PFAL business, system development, and research. Increasingly, PFALs are being developed and operated in Japan and many other countries including Taiwan, China, Singapore, other countries in Asia, the United States, and countries in Europe, etc. Occasionally, the terminology differs among countries or organizations, such as the use of the terms PFAL, vertical farm, indoor agriculture, city farm, etc. The term PFAL as used in this chapter means “an environmentally controlled plant production system with artificial lighting in a thermally insulated, airtight facility.”

From a historical perspective, Japan has been conducting PFAL research since the 1970s. In terms of commercialization, after initial growth in the 1980 and 1990s, the country has experienced a third “boom” in commercial PFALs since 2009, with approximately 200 commercial PFALs operating in Japan (Kozai et al., 2016). Furthermore, and specifically since 2017, the industry can be described as shifting into the fourth movement, which includes scalability and introduction of new technologies such as automation and artificial intelligence, among others. In this chapter, selective PFALs, which are operating economically and sustainably in Japan, including 808 Factory and Spread, and the newly designed system (hardware and software) of PlantX are introduced. This chapter is mainly facilitated through the author’s field work and details are shown in Table 30.1.

30.2 New PFAL built in 2017 in Japan—808 factory

30.2.1 Company outline, vision, and mission

The Japanese company Shinnippou Ltd.¹ established their first “808 Factory” in 2014 which has since become one of the largest PFALs in Japan. Their second 808 Factory was started in 2017, also in

¹<https://www.808factory.jp/>.

Table 30.1 Methodology: Field work conducted by the author and sources for Chapter 30.	
808 Factory, Shinnippou	Information provided by Shinnippou during author's visits to 808 Factory (December 22 in 2017, January 24, October 11, and December 4 in 2018, January 22 in 2019), personal communications (July 25 and 30 in 2018, March 8, 13, 18, and 19 in 2019) and lecture material provided by Shinnippou, "case study of commercial large-scale PFAL, 808 factory" for five-day introductory training course on PFAL at Japan Plant Factory association on October 2, 2018
Spread	Information provided by Spread via questionnaire response (August 10 in 2018), personal communications (October 31, November 1, and December 14 in 2018, March 15 in 2019), and public data
PlantX	Information provided by PlantX via questionnaire response (August 15 and 16 in 2018), personal communications (March 20, 2019), and lecture material provided by PlantX, "Features of Culture Machine with new design concept and future direction (in Japanese)" at the 125th workshop at Japan Plant Factory association on November 14, 2018

Shizuoka Prefecture, located approximately 200 km from Tokyo (Fig. 30.1). Through comprehensive approaches combining their expertise in fields that include agriculture, engineering, IT, and social communication, they have accumulated data-driven knowledge in large-scale production in an efficient, consistent, and sustainable manner.

The "808" in their factory brand name is derived from the Japanese words Ya (eight) – O (zero) – Ya (eight) or YAOYA, which means vegetable/produce store. They promote their ready-to-eat vegetable products by introducing 808 good things and fun facts about their products through online platforms, TV commercials, and practical activities in their local communities.



FIGURE 30.1

Exterior view of the 808 Factory and solar panels.

(Photo courtesy of Shinnippou).

808 Factory is actively developing smart PFALs for the next generation with a vision of enhancing people's health and wellbeing through technically and economically sustainable plant production and introducing their vision to the world.

30.2.2 History and technical background of the company

Shinnippou was founded in 1972 to focus on recreation and leisure including pachinko (Japanese pinball), the hotel business, and solar power generation. In 2012, motivated by challenges faced by modern society, such as declining local agriculture, aging farmers, and an abnormal climate, they established an agriculture department to start their PFAL business with the aim of sustainably growing healthy food unaffected by the weather. They acquired the existing PFAL in 2012, and in 2014 they founded their first 808 Factory, which produces 10,000 heads of lettuce per day. This was followed by their second PFAL, opened in 2017, with additional daily production of 10,000 heads, making their total production capacity 20,000 heads of lettuce per day.

30.2.3 Business features and business model

Shinnippou's PFAL business model is to continue with reliable mass production in PFALs and to distribute their produce while communicating directly with local communities (Fig. 30.2). In addition to operating their PFALs, they have also been developing PFAL-related systems. In fact, their second PFAL, including the cultivation systems, is an in-house design.

One of their major features is that they have generated and utilized big data while commercially producing products since 2014. Taking advantage of the sensing technology of their amusement business, and their understanding of the essence of PFAL engineering, they excel at data-driven sustainable operation of PFALs, which increases their competitive advantages. Specifically, their advantages include (1) operational technique of ongoing stable mass production; (2) continuous improvement of



FIGURE 30.2

Lettuce grown under LEDs at the 808 Factory.

(Photo courtesy of Shinnippou).

productivity and resource use efficiency (RUE); (3) hygienic conditions to secure the safety of their ready-to-eat heads of lettuce, which are packed immediately after harvesting without rinsing; and (4) marketing, branding, and social communication with local communities supported by their data. In addition to operating commercial PFALs, they run two “808 cafes,” one next to a hotel that they own and the other inside a department store, where smoothies made with their PFAL-grown lettuce are served.

30.2.4 Main crops and product brand name

Among the multiple crops being tested in their PFALs, they focus on four kinds of leaf lettuce for sale: frill lettuce, green leaf lettuce, silk lettuce, and romaine lettuce. It is estimated that frill lettuce currently accounts for over 50% of their total sales.

Their produce is harvested and packed daily, while meeting the food industry’s requirements of safety and hygienic control. Every day, 20,000 heads of lettuce are shipped to supermarkets, retailers, restaurants, and food service companies (for bento lunch boxes, sandwiches, sushi, etc.) mainly in the Kanto region (i.e., the Greater Tokyo Area that encompasses seven prefectures) and the Chubu region (i.e., the central region including Shizuoka, their local area) (Fig. 30.3A and B). As of 2018, the retail price is typically 198 yen/80 g package.

The company has successfully raised their brand awareness in the region through continuous advertising campaigns with a playful touch, including TV commercials featuring a famous child actress.

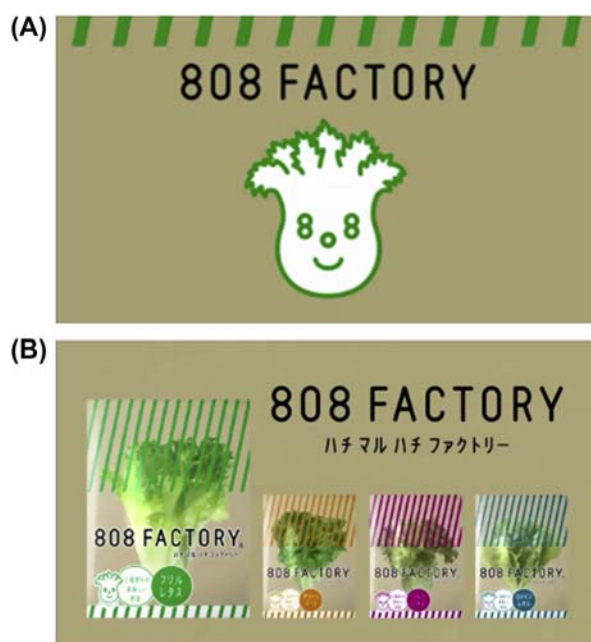


FIGURE 30.3

808 Factory logo (A) and packaged products (B).

(Photo courtesy of Shinnippou).

30.2.5 Outline of PFALs: first and second facilities of the 808 Factory

Their first and second PFALs are located at the same site together with a solar power plant that generates 500 kW of electricity. In addition to the solar power plant, the rooftops of each PFAL and the 100 m² office building are also equipped with solar panels that generate an additional 200 kW of electricity.

The outlines of the first and second PFALs are shown in Table 30.2. Both PFALs are highly insulated, airtight facilities designed specifically for PFALs. They are connected on the inside and each has a cultivation area of 1000 m² consisting of two cultivation rooms of 500 m² in each PFAL. The first PFAL also has a washing room, a storage room, and a visitors' room in addition to the two cultivation rooms. The second PFAL has two cultivation rooms, a seedling production room, two machinery rooms, a packaging room, a chilled room, and a shipment room. Careful sterilization processes are required when entering the factory, including passing through an air shower room.

Their second PFAL was designed in-house, and the cultivation racks, methods, nutrient solution system, automated system, and other features are different from the first PFAL (Figs. 30.4 and 30.5). In addition to the cultivation rooms, there is also an environmentally controlled seedling production room for processes such as sowing, germination, and seedling production. Then after being automatically transplanted by a transplanting robot, plants are moved to the cultivation rooms for additional seedling production and maturing process before harvesting.

The cultivation rooms of the second PFAL are 6 m high and the cultivation racks are 1.4 m wide × 15 m long with 12 tiers equipped with LEDs. On each tier, 60 cultivation panels continuously move at 1.0–1.5 m per day, reaching the other end in 10 or 15 days where the lettuce is harvested daily. In this PFAL, the nutrient film technique (NFT) method is used for cultivation, and the designed nutrient control system can control each rack individually. As for the water source, quality groundwater is used for the entire process, including cleaning and washing cultivation panels.

In terms of automation, transplanting robots were developed in-house. Each robot can transplant four plants at a time (2000 plants/h per machine) without damaging the plants or roots, as shown in Fig. 30.6. All the circulation pumps and nutrient solutions are placed in the machinery rooms in the second PFAL, separated from the cultivation rooms for ease of maintenance (Fig. 30.7).

30.2.6 Technical characteristics

As mentioned earlier, one of the major technical characteristics of the 808 Factory is high-quality big data, generated through actual commercial operation while consistently growing high-quality products in a thermally insulated, airtight facility. By utilizing multiple sensors, different types of cameras, and various tools, environment and management (operation) data are collected and analyzed together with the growth data.

In terms of the environmental data, in addition to continuous and automated measurements of the air and nutrient solution environment 24/7/365, additional data collected include PPFD, thermography, wind velocity, and elements in nutrient solution. Photosynthetic rate and stomatal conductance are occasionally measured with the appropriate device to capture growth data (i.e., phenotypic traits). Given these datasets and the careful observation of plant growth, plus the company's environmental control techniques, 808 Factory is expected to achieve their growth targets for consistent mass production.

Table 30.2 Outline of PFALs: First and second facilities of the 808 Factory.

Plant factory name	808 Factory
Location	Yaizu, Shizuoka, Japan
Month/year of initial sales ^a	PFAL1: March 2014, PFAL2: April 2017
Land area	10,000 m ²
Floor area of PFAL building	PFAL1: 1400 m ² , PFAL2: 1600 m ²
Daily production capacity	PFALs 1 and 2: 20,000 heads (80 g/head) of lettuce
PFAL operating rate	PFALs 1 and 2: Full operation
Cultivation room	Floor area^b Cultivation area Ceiling height No. of racks and tiers^c Distance between tiers^d Width and length of each rack Distance between racks (aisle width) Cultivation beds Light source
Substrate (supports)	PFAL1: 1000 m ² (500 m ² × 2 rooms) PFAL2: 1000 m ² (500 m ² × 2 rooms)
Produce without roots	PFAL1: 3600 m ² , PFAL2: 3456 m ²
Automation in PFALs 1 and 2	PFAL1: 4.5 m, PFAL2: 6.0 m
	PFAL1: 20 racks, 10 tiers, PFAL2: 16 racks, 12 tiers
	(1) PFAL1: 0.34 m, PFAL2: 0.4–0.42 m (2) PFAL1: 0.22 m, PFAL2: 0.24–0.28 m
	PFAL1: Width: 1.4 m, length: 15 m PFAL2: Width: 1.4 m, length: 15 m
	PFAL1: 0.6 m PFAL2: 0.5 m
	PFAL1: DFT (deep flow technique) PFAL2: NFT (nutrient film technique)
	PFAL1: Originally fluorescent lamps but replaced with LEDs in 2017; PFAL2: LEDs
	PFALs1 and 2: Foam urethane cube
	Yes
	Manual: Harvesting. Manual/semiautomated: sowing. Automated: transplanting (developed in-house), packing. Automated only in PFAL 2: Conveying system

^aInitial sales includes trial sales.

^bFloor area of cultivation rooms of PFALs 1 and 2 excludes area for sowing, seedling production, and transplanting.

^cTiers are also referred to as “layers.”

^d(1) indicates vertical distance between frames of the rack, (2) indicates vertical free distance from the bottom of lights to the cultivation panel.

Source: Based on information provided by Shinnippou during author's visits to 808 Factory (December 22 in 2017, January 24, October 11, and December 4 in 2018, January 22 in 2019), personal communications (July 25 and 30 in 2018, March 8, 13, 18, and 19 in 2019) and material provided by Shinnippou, “Case Study of Commercial Large-scale PFAL, 808FACTORY” for Five-day Introductory Training Course on PFAL at the Japan Plant Factory Association on October 2, 2018.



FIGURE 30.4

Interior view of the cultivation room with multitier racks in the second PFAL.

(Photo courtesy of Shinnippou).



FIGURE 30.5

Interior view of the cultivation room of the second PFAL.

(Photo courtesy of Shinnippou).



FIGURE 30.6

Transplanting robot developed in-house.

(Photo courtesy of Shinnippou).



FIGURE 30.7

Machinery room with the circulation pumps and nutrient solutions.

(Photo courtesy of Shinnippou).

Moreover, a security video camera and a web camera are used to capture management data for remote monitoring and observing operations such as time taken for each production process in order to optimize the operational management. As there are approximately 30 workers on average involved in daily production, the improvement of operational flow and labor management has helped reduce labor costs. Moreover, to manage the hygienic conditions, microorganisms and pests are monitored as well as many other factors.

In the packaging room, there are five packaging lines equipped with auto filming machines, metal detectors, and automatic weight checkers (Fig. 30.8). All packaged products are transported to the

**FIGURE 30.8**

Interior view of the packaging room.

(Photo courtesy of Shinnippou).

neighboring chilled room by a conveyor. On the packaging line, the weight, production number, and other data are automatically collected using their weight-check system, which contributes to the analysis of the product weight and variability among the plant products (Shinnippou, 2018). In addition to monitoring of the product weight, product waste is also monitored, which enables analysis of the daily RUE.

30.2.7 Future plans

While there are currently no specific major problems in operating their PFALs, according to the manager of the 808 Factory, the company excels at continuously improving their technologies and productivity to achieve the ideal smart PFAL. Regarding human resources, they intend to hire additional specialists for staff training, factory management, data analysis, product management, etc. In terms of the cultivation processes, the identification and selection of suitable seeds for PFALs are among their most specific interests.

808 Factory is planning to develop their third PFAL, a smart 808 factory, where they aim to apply artificial intelligence together with maximum utilization of their big data, fully automated systems, and phenotyping technologies, while building on their expertise in operational techniques. Future goals include establishing their large-scale smart PFAL and expanding smart 808 Factory systems internationally. They aim to achieve these goals with their know-how in sustainable PFAL operations and successful data-driven social communications with their local communities.

30.3 New PFAL built in 2018 in Japan—Spread

30.3.1 Company outline, vision, and mission

Spread Co., Ltd.² is one of the few companies in the world with more than a decade-long history of commercial operation of a large-scale PFAL. Their first PFAL, established in 2008 in Kyoto, Japan, has a daily production of approximately 21,000 heads of leafy greens. In 2017, they started construction of their second PFAL, Techno Farm Keihanna, a large-scale automated facility with a daily production capacity of 30,000 heads of lettuce (Fig. 30.9).

Spread's mission is to create a sustainable society where future generations can live with peace of mind. Their approach to achieving sustainable farming is based on the following three principles: (1) social nature: ability of consistent and stable production of safe food; (2) economy: ability to secure stable earnings as a sustainable business; and (3) environmental sustainability: ability to conserve resources and the Earth's environment.

Based on these principles, Spread is committed to the "PFAL project" as one of the sustainable farming models by introducing state-of-the-art technologies and creating innovations so that anyone can stably produce high-quality, nutritious food anywhere in the world. Furthermore, in order to establish a "food infrastructure" that will allow equal and fair food supply to all people, they aim to expand their PFAL business globally and pass down sustainable agriculture to the next generation.

30.3.2 History and technical background of the company

Spread was founded in 2006 by the Trade Group (currently Earthside Group), a distribution/logistics company for fresh produce. While handling vegetables on a daily basis, they faced emerging



FIGURE 30.9

Exterior view of Spread's second PFAL, Techno Farm Keihanna.

(Photo courtesy of Spread).

²www.spread.co.jp/en, <http://technofarm.com/innovation/>.

agricultural issues in Japan: aging of farmers, shortage of successors, abnormal weather, etc. They became concerned about the potential decline in productivity of Japanese agriculture. Furthermore, given the global challenges of increasing population, shortage of water and other resources, and increasing environmental load, they felt the need to develop solutions to secure future food supplies. Therefore, with the aim of creating a new agricultural system that is more productive and environmentally friendly, they established Spread Co., Ltd. in 2006 and started their PFAL business to stably produce vegetables that were unaffected by the weather.

30.3.3 Business features and business model

The business activities of Spread include the operation of large-scale PFALs, sales of their produce grown in PFALs, and expansion of various partnerships to build their PFALs internationally. They recently developed their new PFAL system “Techno Farm” based on their 10 years of experience in the field.

One of the primary features of Spread is their comprehensive dynamism that is applied consistently from production to sales, sales promotion, and branding. In addition, taking advantage of the group’s logistics companies that specialize in vegetables, they have been successfully delivering their produce through a nationwide cold chain, while flexibly adjusting the scale based on the needs of the retailers, in an efficient and cost-effective manner.

In terms of their approach to sales, Spread has actively promoted sales activities, since the beginning, such as in-store tasting sales, and has directly demonstrated to consumers the merits of PFAL-grown vegetables even though there was little consumer awareness at the time. They also have an internal design team, which allows them to design packages and items to promote their “Vegetus” brand. Thanks to these ongoing efforts, they currently sell their produce at about 2400 supermarkets nationwide.

30.3.4 Main crops and product brand name

Four kinds of leaf lettuce are grown in their PFALs as main crops: frill lettuce, pleated lettuce, romaine lettuce (cos lettuce), and fringe lettuce. These products are packed and shipped mainly to supermarkets and retailers under the product brand name “Vegetus” (Fig. 30.10). The retail price of their products is approximately 198 yen per package as of 2018.

30.3.5 Outline of PFALs of Spread

As mentioned earlier, Spread has been operating their first PFAL with a daily production capacity of 2000 kg (7.7 million heads yearly) of lettuce, in Kameoka, Kyoto, since 2008. In early November 2018, they officially announced the initial shipment of produce from their second PFAL, Techno Farm Keihanna, a larger-scale automated facility in Kizugawa, Kyoto, the first facility to implement the Techno Farm system (Spread, 2018a). As shown in Table 30.3, Techno Farm Keihanna has a floor area of 3950 m² in a two-story steel construction building. The daily production capacity is 3000 kg of lettuce, which is 1.5 times that of their first factory.

One of the major features of Techno Farm Keihanna is their automated facility. Spread intends to utilize automation technologies throughout the cultivation processes from seedling to harvesting, for which the human workload is especially demanding. Specifically, they use robot arms for transplanting

**FIGURE 30.10**

Product of Spread, with Vegetus brand name.

(Photo courtesy of Spread).

and stacker cranes for automatically moving cultivation panels from the racks (Fig. 30.11). However, this automation system does not include the cutting process during harvesting.

30.3.6 Technical characteristics

During the operation of their large-scale environmentally controlled facilities over the past 10 years, they have accumulated the know-how to improve the labor efficiency including the improvement of work flow lines. Therefore, they achieved a 97% product ratio at the Kameoka plant. Careful planning of the factory operation was initially conducted by calculations from the accepted retail price in the market, production cost, and feasible volume and scale of their facility, together with their business expertise in the distribution of fresh produce by their group companies.

Technical features of Spread's Techno Farm include automated cultivation, environmental control technology, water recycling technology, and IoT/AI technology. Automated cultivation saves labor and keeps the cultivation room unmanned and improves hygienic conditions. Moreover, since human working space or aisles between cultivation racks are not required, each cultivation rack can be more densely placed, and productivity (i.e., efficiency per area) can be increased. As for IoT/AI technology, they are planning to develop a system to achieve advanced production management including yield prediction based on optimum cultivation conditions from cultivation data collected by sensors. In October 2018, Spread announced their partnership with NTT Comware Corporation to jointly develop an IT management platform for Techno Farm (Spread, 2018c).

Table 30.3 Outline of PFALs of Spread.		
Plant factory name		PFAL 1: Kameoka plant, PFAL 2: Techno farm Keihanna
Location		PFAL 1: Kameoka, Kyoto, Japan PFAL 2: Kizugawa, Kyoto, Japan
Month/year of initial sales ^a		PFAL 1: April 2008, PFAL 2: November 2018
Land area		PFAL1: 4780 m ² , PFAL2: 11,550 m ²
Floor area of PFAL building ^b		PFAL1: 2868 m ² , PFAL2: 3950 m ²
Daily production capacity		PFAL1: 21,000 heads (2000 kg) of lettuce PFAL2: Scheduled to be 30,000 heads of lettuce
PFAL operating rate		PFAL1: 100%, PFAL2: not answered
Cultivation room	Cultivation area	PFAL1: 25,200 m ² , PFAL2: not answered
	Ceiling height	PFAL1: 16 m (height of building) PFAL2: Not answered
	No. of racks and tiers	PFAL1: 28 racks, 12 tiers (14 racks) and 16 tiers (14 racks), PFAL2: not answered
	Cultivation beds	PFAL1: DFT (deep flow technique)
	Light source	PFAL1: Fluorescent lamps and LEDs PFAL2: LEDs
Produce without roots		Yes
Automation in PFALs 1 and 2 ^c		PFAL1: Manual: sowing, transplanting, harvesting; Automated: packing PFAL2: Sowing, transplanting, harvesting (only for moving cultivation panels. No automation for cutting process) are scheduled to be automated
Items including, floor area of cultivation room, distance between tiers (layers), width and length of each rack, and distance between racks (aisle width) of cultivation room, and substrate (supports) were not answered by the company.		
^a Initial sales includes trial sales.		
^b Floor area of PFAL building includes R&D area.		
^c Automation in PFALs 1 and 2.		
Source: Based on information provided by Spread via questionnaire response (August 10, 2018), personal communications (October 31 and November 1, 2018, March 15, 2019), and public data (Spread. 2018b. Technology, the Kameoka Plant's Performance. Retrieved March 5, 2019 from: http://www.spread.co.jp/en/technology/).		

30.3.7 Challenges

In order to expand their distribution in the domestic commodity market, they intend to reduce costs while maintaining high quality. PFAL-grown lettuce is generally two to three times more expensive than field-grown lettuce, depending on the season and the market price of field-grown produce. Spread intends to reduce the cost through mass production at a large-scale PFAL. Moreover, for the global market, they consider it important to raise market awareness of the benefits of PFAL-grown produce in each target region. Given the increasing attention to PFALs in terms of ESG (environment, social, governance) and sustainable agriculture in recent years, Spread's long-term goal is to improve the

**FIGURE 30.11**

Stacker crane for loading panels automatically.

(Photo courtesy of Spread).

sustainability of PFALs by applying new methods and materials such as utilizing renewable energy and reviewing new cultivation media and packing materials.

30.3.8 Future plans

While Spread's current major market is Japan, they intend to expand into global markets such as North America, Europe, and the Middle East. As for research and development, besides general technical development, they aim to develop cultivation techniques suited for a wider variety of leafy vegetables, and to develop products according to the local market needs.

Spread will pursue collaboration and building relationships with domestic and overseas partners in order to promote the development of the "Techno Farm." To achieve domestic and global expansion, they aim to develop multiple partnership models by understanding the needs of each partner and incorporating their mutual goals. Their partnership models include franchise and ownership models. By 2025, Spread envisions achieving the production of 500,000 heads of lettuce per day within Japan, and, in the long term, they aim to build their PFALs in multiple locations around the world to establish a food infrastructure.

30.4 New PFAL system developed in Japan—PlantX

30.4.1 Company outline, vision, and mission

PlantX Corp.³ is a venture company founded in 2014 in Kashiwa, Chiba Prefecture, Japan, with the focus of providing technologies and services related to PFALs. They initially developed a production process management system, SAIBAIX, and then commercialized their proprietary cultivation system module, Culture Machine (Fig. 30.12).

Through a precisely controlled cultivation environment in an enclosed space, PFALs allow the company to stably produce plants with the maximum yield and the highest quality with the minimum resources, energy, and pollutant emissions. With the increasing severity of agriculture-related problems worldwide, such as water shortages, agricultural land degradation and desertification, declining proportion of farmers, and unstable production due to abnormal weather, PFALs are drawing attention worldwide as a new production method for future generations. Furthermore, by developing more high-value plants, plants are expected to be used in a variety of fields such as medicine and cosmetics.

However, there are still practical technical challenges that need to be solved, including more precise environmental control and process management with higher resource use efficiency. By overcoming these problems, the company aims to maximize the potential possibilities of PFALs and increase their use around the world, and eventually to create new values for food and agriculture.



FIGURE 30.12

Cultivation system module (Culture Machine) of PlantX.

(Photo courtesy of PlantX).

³<http://www.plantx.co.jp/>.

30.4.2 History and technical background of the company

PlantX aims to establish PFAL production technology that applies the technology of industrial factories. Among the founding members are electric/electronic engineers who have developed medical equipment with major manufacturers, and an information technology engineer who has developed process control systems for industrial factories.

By implementing plant growth management software and consulting for other large-scale PFALs in Japan, they have rapidly improved yields (in one example, doubling the yield in 4 months, according to PlantX). Furthermore, engineers from the automobile manufacturing industry have joined the company for the development of a proprietary cultivation module system.

Their current major business is to sell their own software and hardware systems and provide consultancy services, including business planning, factory design, and operational support. Since their plant growth management software is a cloud-based platform, their customers are able to continuously receive the latest cultivation techniques.

30.4.3 Technical characteristics

To date, the company's plant growth management software, SAIBAIX, and cultivation system module, Culture Machine, are being developed in-house for commercialization. The features of each are described below.

1. Production growth management system (SAIBAIX)

This system consists of sensors, software, and a controller. A real-time display function for sensor measurement values, cost index values, and plant growth index values together with an alert function are provided (Fig. 30.13). In addition to state variables of the cultivation environment (temperature, humidity, CO₂ concentration, ion concentration in nutrient solution, etc.), it is also



FIGURE 30.13

Multiple monitors for the production process management system (SAIBAIX).

(Photo courtesy of PlantX).

possible to monitor rate variables (photosynthetic rate, nutrient solution ion uptake rate, water uptake rate, etc.) including plant growth rate, and to estimate the RUE almost in real time (Kozai, 2018). They believe that the value of PFALs comes from the growth of the plants. Therefore, a system that controls plant growth is essential.

2. Cultivation system module (Culture Machine)

One of the unique features of this proprietary cultivation device is that the cultivation system is sealed individually for each device with thermally insulated airtight boards. Since this is an independent module system, each system can individually control the environment of each tier, such as the light, air, water, etc. Furthermore, various control devices for LEDs, nutrient solution circulation, air conditioning, etc. are installed within the module. This greatly improves the controllability of the system. It is expected that this scalable production system is suited for mass production in PFALs or as experimental equipment, where the system is expected to demonstrate high performance while achieving reproducibility and scalability. The size of the existing current system, Culture Machine Type S, is 1.8 m wide $\times$ 7.7 m long $\times$ 3 m high (PlantX, 2018). It consists of four cultivation tiers with a distance of 0.5–0.6 m between each tier. The NFT method is used for cultivation, and the nutrient solution is circulated. A foam urethane cube is currently used as the cultivation substrate. An automated transporting system is used for moving cultivation panels.

30.4.4 Future plans

They aim to accumulate their experience in PFAL construction and operation first in Japan, and then expand abroad, including North America, in the future. Moving forward, they intend to continue designing, operating, and proving their system's performance, particularly in a large-scale PFAL. Specifically, they are developing a larger scale Cultivation Machine, a 20 m long and 6 m high system.

They intend to further develop their cultivation system and plant production process management software, targeting wider varieties of crops to identify the ultimate setpoints of environmental control. They aim to analyze data together with the growth models installed in their software and artificial intelligence and phenotyping in the future to maximize results.

30.5 Conclusion

Moving toward the next generation, the fourth movement of PFAL in Japan will increase the use of machine learning, breeding techniques, and other dynamic technologies. Since 2017, research projects have been conducted in Chiba, Japan, on artificial intelligence and phenotyping-based environmental control and breeding for PFAL, along with the development of a new cultivation system module (Kozai, 2018). It is expected that some commercial PFALs are getting ready to actively utilize phenotyping technologies while generating high-quality data from the operation of commercial PFALs. Together with collaboration and knowledge sharing in the industry, PFALs with a growth initiative in Japan are committed to enhancing the productivity and stability of plant production and achieving technically and economically sustainable next-generation smart PFAL.

Acknowledgments

The author expresses deep gratitude to Katashi Kai (General Manager, 808 Factory, Shinnippou), Hiroumi Takahara (General Manager, Spread), Minako Ando (Spread), Kosuke Yamada (Founder and CEO, PlantX) and Shunsuke Sakaguchi (Founder and Director, PlantX) for their cooperation and openness to providing information. The author also appreciates the technical guidance of Toyoki Kozai (Japan Plant Factory Association).

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Representative plant factories in Taiwan

31

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31.1 Introduction

To produce ready-to-eat (RTE) and ready-to-cook (RTC) leafy greens, a plant factory with artificial lighting (PFAL) needs to be kept at the same conditions as a standard clean room, which is normally equipped with the following “essential five (E5)” items: epoxy flooring, airtight thermally insulated roof and walls, air shower, air conditioner, and CO₂ enrichment system.

31.2 Representative PFALs in Taiwan

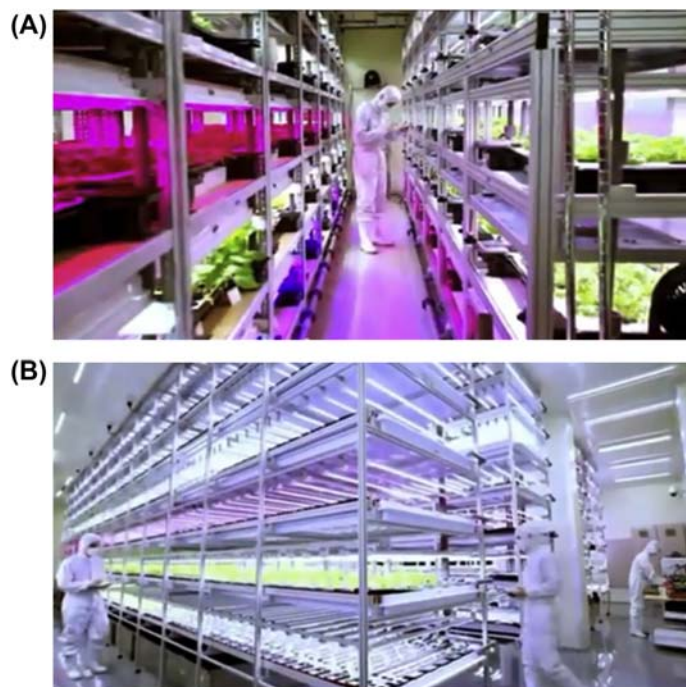
As of 2019, most of the 136 organizations engaged in PFAL research and/or business were equipped with the E5 items mentioned above. Among these organizations are three companies with distinctly different business models: Cal-Com Bio Corp., Glonacal Green Technology Corp., and Tingmao Agricultural Biotechnology.

Taiwan’s largest plant factory (PF), which uses lamps but is not a PFAL, is Yasai Lab Corp. None of the E5 items are used in the PF due to different design concepts. Yasai Lab focuses on producing eat-after-wash (EAW) and cook-after-wash (CAW) leafy greens and is introduced in a later section.

31.2.1 Cal-Com Bio Corp. of the New Kinpo Group

This company produces leafy greens and medicinal herbs for members only at two locations. Daily production of their first and second PFALs is 100 and 1000 plants per day, respectively (Fig. 31.1A and B).

This company is unique in that it is the only PFAL company in Taiwan with ISO-9001 and ISO-22000 certification. The company also uses a seeding robot, which was developed in-house, and a semiautomatic packaging machine.

**FIGURE 31.1**

(A) First PFAL of Cal-Com Bio Corp., Taiwan. (B) Second PFAL of Cal-Com Bio Corp., Taiwan.

31.2.2 Glonacal Green Technology Corp

In addition to its PFAL construction/consulting business, Glonacal Green Technology also produces leafy greens that are sold to local 4- and 5-star restaurants. Daily production at the demo room is around 400 plants (Fig. 31.2A). Fig. 31.2B shows a window view of the demo room, in which can be seen a light-mounting frame with adjustable hanging strings. The strings make it possible to manually adjust the distance from the lights to the plants.

This company is unique in that it has a patent for the movable light-mounting fixtures. The lights can be moved in either the horizontal or vertical direction when necessary. Also, the patented integrated design of the bench handles the production system, the artificial light, the air flow movement, the controls for the light cycle and nutrients, and the measurement of environmental factors as a whole. Each bench is a stand-alone unit, which not only eliminates the risk of cross-contamination, but also allows leasing of the equipment. The stand-alone design means that there are no pipes or electrical wires on the floor or between the benches, making it easy to clean the floor and transport items using carts.

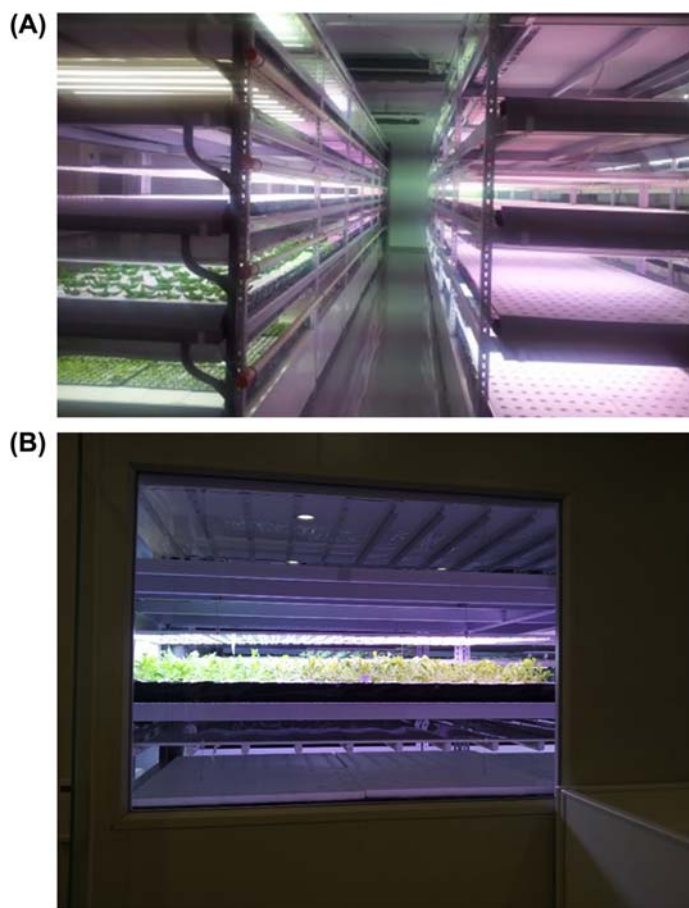


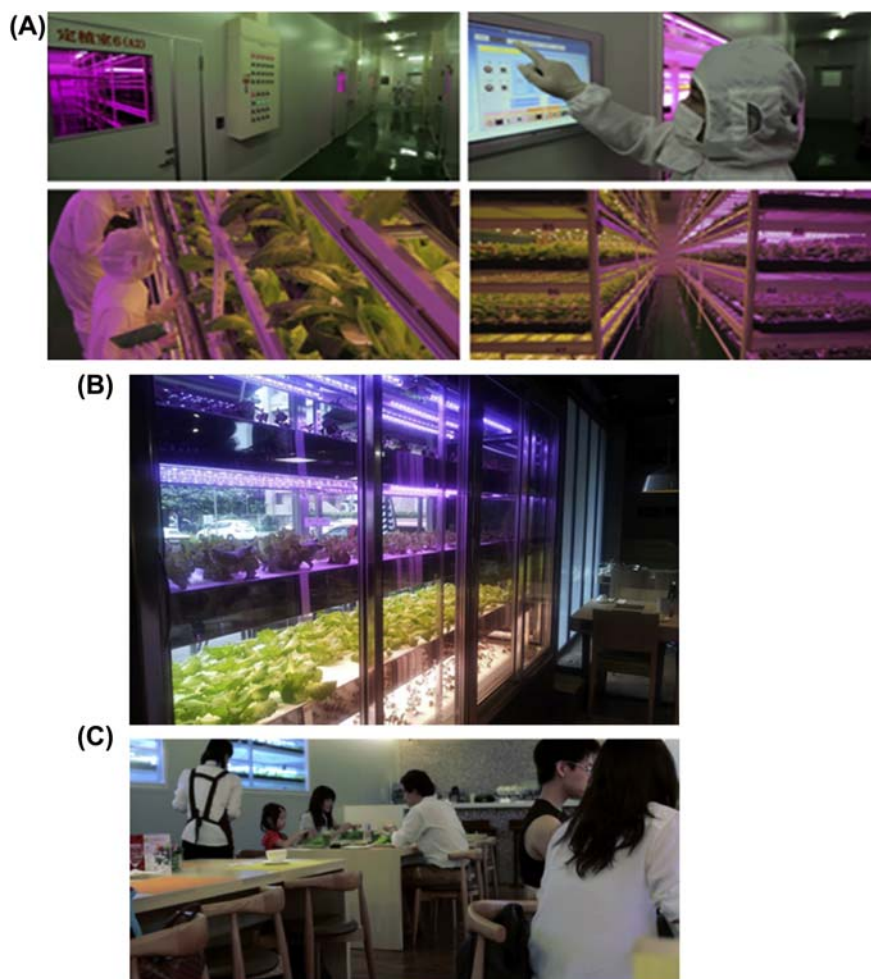
FIGURE 31.2

(A) Demo room of Glonacal Green Technology Corp., Taiwan. (B) Window view of the demo room of Glonacal Green Technology Corp., Taiwan.

31.2.3 Tingmao agricultural biotechnology

This company has a mass production center (floor area around 3300 m², Fig. 31.3A) and 14 “Nice Green Kitchen” restaurants, six of which are equipped with culture benches and a demo room (132 m²) for small-scale production (Fig. 31.3B and C).

A unique feature of Tingmao Agricultural Biotechnology is that it has multiple sales channels for its products, including: (a) websites for the general public and members; (b) chain restaurants for members; (c) membership exchange with other health-related organizations such as yoga clubs; and (d) various lines of processed products developed with PF-grown vegetables as add-in ingredients. These processed products, all with vegetable ingredients, can be categorized into three groups: (1)

**FIGURE 31.3**

(A) Four views of the mass production center of Tingmao Agricultural Biotechnology, Taiwan. (B) One of the “Nice Green Kitchen” restaurants and CE bench style PF demo facility of Tingmao Agricultural Biotechnology, Taiwan. (C) One of the “Nice Green Kitchen” restaurants and PF concept demo room of Tingmao Agricultural Biotechnology, Taiwan.

health food supplements such as vegetable powder, concentrated tablets and noodles, bread, egg rolls, and ice cream with vegetable ingredients; (2) skin care products such as soap for the skin, hair, and scalp, and facial masks; and (3) “green latte” beverages, which can be mixed with various fruits, nuts, and herbs to produce different tastes and flavors. One unique product is frozen immediately after production and it takes 30 min for the consumer to defrost it. According to a company official, this product unexpectedly turned out to be a best seller.

31.2.4 PFAL building inside a greenhouse

Most of the PFALs in Taiwan are equipped with the E5 items described earlier, with two exceptions—Lee-Pin and Yasai Lab. Details about Yasai Lab are provided in the next section. Lee-Pin uses a gutter-connected greenhouse as their PF enclosure with internal fans and roof vents and retractable internal shade curtains to block excess sunlight. It is located within a paddy field in Dan-Sui (on the northern tip of Taiwan), as shown in [Fig. 31.4A](#).

The current monthly production at Lee-Pin is about 5000 kg of produce, which is mainly sold to the nearby community residents. The PF is equipped with 12 rows of benches that are each 15 m long and have six tiers per bench. The upper tier relies on sunlight and the bottom five tiers use artificial light. Inside the greenhouse is epoxy flooring, as shown in [Fig. 31.4B](#). The seedling production area with the air conditioning system and the work area are in the fixed shade zone at the front end of the greenhouse, as shown in [Fig. 31.4A](#).

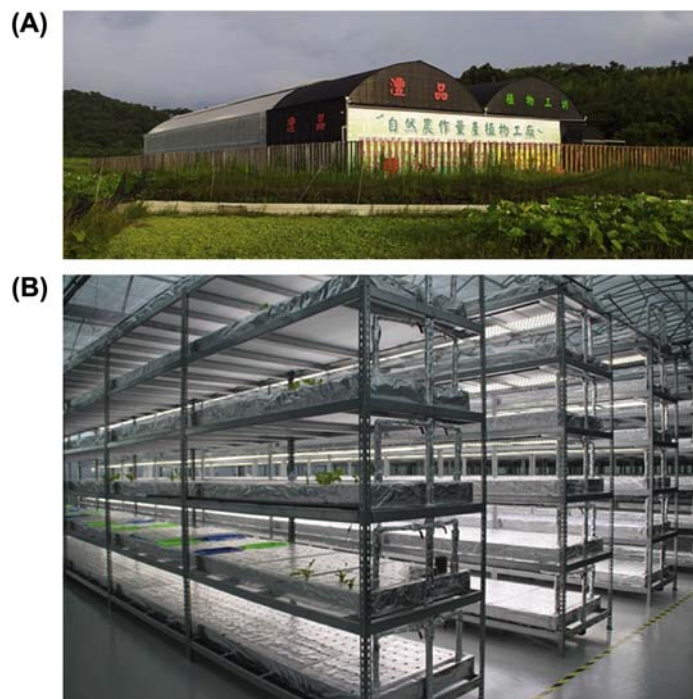


FIGURE 31.4

(A) Exterior view of the plant factory located in a paddy field, Lee-Pin Corp., Taiwan. (B) Interior view of the plant factory located in a paddy field, Lee-Pin Corp., Taiwan.

31.3 The largest PF in Taiwan

Yasai Lab Corp. renovated an industrial factory for its PF enclosure. It is currently the largest PF with lamps (but not a PFAL) in Taiwan and perhaps in the world in terms of full-scale daily production. None of the E5 items are used in this PF; a pad and fan system is used instead of air conditioning for cooling, thus limiting production to seasonal crops, and the indoor humidity is normally high, leading to a slow growth rate compared with that in PFALs.

This company produces CAW and EAW leafy vegetables, which are sold through supermarket channels. The strategy is to sell at the lowest price (200 NT\$/kg) compared with PFAL companies (500–2000 NT\$/kg) (1 US\$ = 30 NT\$ as of 2018). At that low price, it is nearly impossible to recoup the cost. As price is a major concern for consumers, such low-priced pesticide-free products are extremely attractive and competitive.

The dimensions of Yasai Lab's PF are $60 \times 30 \times 8$ m. The total height of the benches is 7 m, consisting of six seedling benches with 16 tiers each and 31 benches with 10 tiers each for mature-stage production. In full operation, the facility can handle 1.8 million plants at the same time and daily production is around 2500 kg per day, with 60,000 plants harvested per day when in full operation.

As shown in the upper part of Fig. 31.5A, Yasai Lab uses pink LED panels. The panels can be moved horizontally, providing a maximum of 12 h of light for all crops. Several types of automatic equipment are used, such as a seeding machine for coated seeds and a transplanting machine, as shown in the bottom part of Fig. 31.5A. The conveyors for vertical and horizontal movement of the growth panels are shown in Fig. 31.5B. The company also has root cutters and root pressers to reduce the size of waste. Surprisingly, automatic or semiautomatic packaging machines are not used.

Unfortunately, due to the wrong business model and poor engineering design of the related hardware, this company is no longer in business. The former general manager, Mr. Tsai, established another company, Yuan Hsien Agri-Bio Science and Technology Corp., which operates the YesHealth iFarm located in northern Taiwan, close to Taoyuan International Airport. YesHealth is the biggest plant factory in Taiwan. The design is almost exactly the same as that at Yasai Lab, still using the pad and fan system for cooling and without an air conditioning system in the culture area. Vertical transport of the floating panels is also the same, as shown in Fig. 31.6A. On-site harvesting and packaging can be seen by visitors to the YesHealth iFarm, as shown in Fig. 31.6B. There are three major differences between Yasai Lab and YesHealth.

First, YesHealth uses organic liquid fertilizer instead of chemical fertilizer in their hydroponic system. According to Taiwan's regulations, the company cannot label their produce as an organic product, but this has not deterred customers, who are happy with the products as long as they are guaranteed to be free of pesticides, herbicides, and heavy metals. Safety is a bigger issue than organics for consumers in Taiwan.

Second, YesHealth applies nanobubbles to the nutrient solution to enrich dissolved oxygen. Using the deep flow technique (DFT), if the root zone is totally submerged in the solution, it is easy to encounter a low dissolved oxygen situation, which is stressful to the plant. According to the tour guide, the application of nanobubbles prevents this dissolved oxygen deficiency problem.

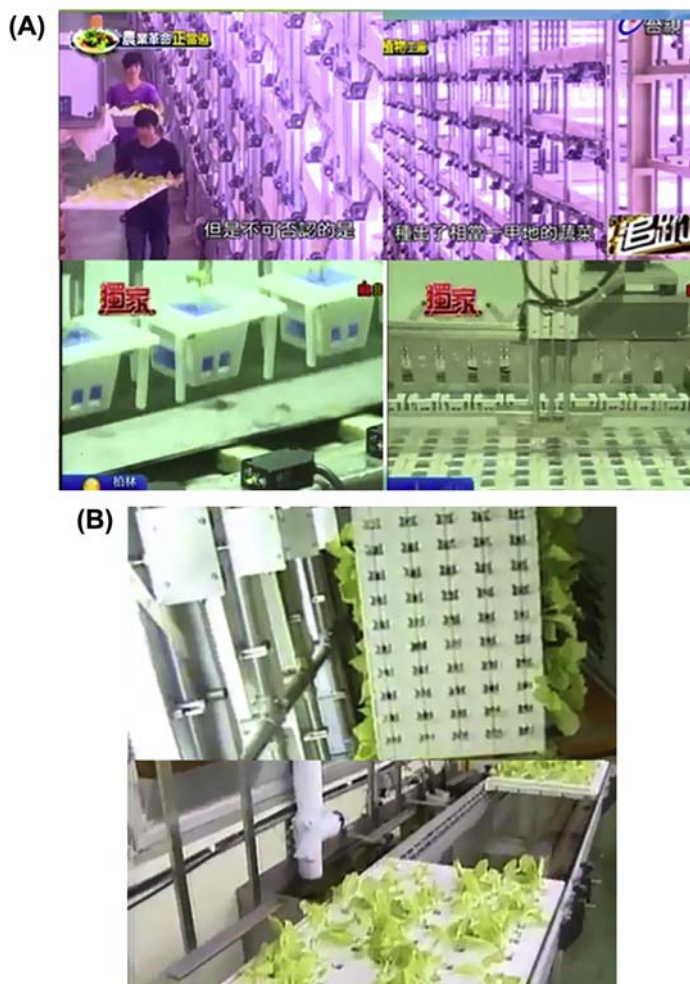


FIGURE 31.5

(A) Illuminated benches at Yasai-Lab's PF and operation of transplanting device. (B) Automatic transfer of growth panels in vertical and horizontal directions at Yasai-Lab Corp., Taiwan.

Third, YesHealth operates a restaurant for light meals and a sales division for selling their produce to tourists. The “iPaleo” restaurant is located next to the production site and the “iShopping” center for tourists is close to the exit from the facilities. This difference has attracted public media and consumers, making YesHealth quickly well-known and allowing consumers to learn about PFs and the beneficial features of PF produce without the company having to invest in advertising. Opening a

**FIGURE 31.6**

(A) Vertical transport of floating panels at YesHealth iFarm. (B) On-site harvesting and packaging at YesHealth iFarm.

restaurant, inviting consumers to tour the site, allowing children into the production site, and experiencing several hours as an i-farmer is a popular business model for large-scale PFALs in Taiwan. So far, the operation looks promising and is attracting venture capital. The company helped Foxconn (another Taiwanese company) build a PFAL in Shenzhen, China, which was completed in May 2018. The floor area is 5000 m² and daily production is 2500 kg of vegetables. The benches for seedling production have 16 tiers and those for mature plant production have 14 tiers. The floor area might not be the biggest in China, but the daily production volume is the largest. SananBio's PFAL located in Anxi County, Fujian Province, China, has a floor area of 10,000 m², which is double that of Foxconn's PFAL, but the daily production is merely 1500 kg, 60% of Foxconn's. The main reason might be that SananBio's culture benches have only six tiers each. According to news reports, YesHealth is planning to build a PFAL in the United Kingdom.

Challenges for the next-generation PFALs

32

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32.1 Introduction

Plant factories with artificial lighting (PFALs) technology is multidisciplinary, and PFALs provide a unique environment for growing plants. Much of PFAL technology differs from that used in horticulture and agriculture, although the basic science and technology are the same. Thus, new ideas for developing PFAL technology are needed.

This chapter describes examples of such ideas, including: upward lighting systems, use of green LEDs, breeding of vegetables, and medicinal plants suited to PFALs, seed propagation, a hydroponic culture system with restricted root mass, year-round production of ever-flowering berries, use of natural energy in PFALs, and data mining using big data. The ideas described below are meant to encourage the next generation of scientists to approach conventional horticultural technologies with new ideas and fresh methods.

32.2 Lighting system

32.2.1 Upward lighting

The photosynthetic rate of a whole plant is generally highest when the light energy is equally absorbed by the entire leaf surface assuming that the photosynthesis curve as affected by photosynthetic photon flux density (PPFD) is identical for all the leaves of the plant.

When solar or artificial light energy is given downward to a densely populated plant community, most light energy, especially red and blue light energy, is absorbed by the upper leaves, while the PPFD reaching the lower leaves is often nearly equal to or lower than the light compensation point and hence the net photosynthetic rate of the lower leaves is equal to or lower than 0. This is why the lower leaves of a densely populated plant community often become yellow-colored, shrink, or die. Under such low PPFD conditions, lower leaves tend to exhibit characteristics of shade leaves with low light saturation intensity.

In order to mitigate this uneven vertical distribution of light energy over the upper and lower leaves, intercrop (sideward) lighting using LEDs is becoming popular for greenhouse crops such as tomato and rose plants in winter as well as on cloudy or rainy days in order to provide more light energy to the lower leaves. Sideward lighting was also tested on photoautotrophic plant micropropagation (Kozai et al., 1992).

In the PFAL, upward lighting using LEDs placed on the culture panels to provide more light energy to the lower leaves of leafy greens should be more beneficial than intercrop lighting (Zhang et al., 2015; Kozai et al., 2016). In the PFAL, upward light not absorbed by lower leaves is absorbed by upper leaves or reflected back downward to the plant community by the light reflector placed above the plant canopy, to minimize the loss of upward light energy emitted from the LEDs (Fig. 32.1; Kozai, 2012). However, the upward lighting system might modify the plant morphology, physiology, and anatomy to some extent, possibly leading to new research subjects and applications. The development of an innovative lighting system specifically for PFALs is awaited.

32.2.2 Using green LEDs

The photosynthetic rate of a leaf is directly related to PPFD, not to the PAR energy flux density (Chapters 9–13). It is often said that, in a PFAL, red light (wavelength: 600–700 nm) is most effective for promoting photosynthesis of plants but some blue light (400–500 nm) is necessary mainly for photomorphological and/or phytochemical reasons for a given amount of electric energy consumption. This is because the light energy contained in one photon is inversely proportional to the wavelength. Therefore, the light energy per photon is 1.2 ($= 600/500$) to 1.75 ($= 700/400$) times higher in a blue photon than in a red photon.

It is well known that a thin layer of chlorophylls suspended in a liquid absorbs red and blue photons very well but absorbs little or no green photons. It is also known that a single green leaf absorbs about 50%, reflects about 20%, and transmits about 30% of green photons. These figures are for a thin layer of chlorophylls and a single leaf, respectively, not the whole plant community.

When plants are densely populated, most green photons transmitted by the upper leaves will be received by the lower leaves. In a PFAL, green photons reflected upward by the leaves are again reflected back downward by the light reflector to the plant community and are received by the leaves. As a result, most green photons emitted by the LEDs are received by the plant community vertically more evenly

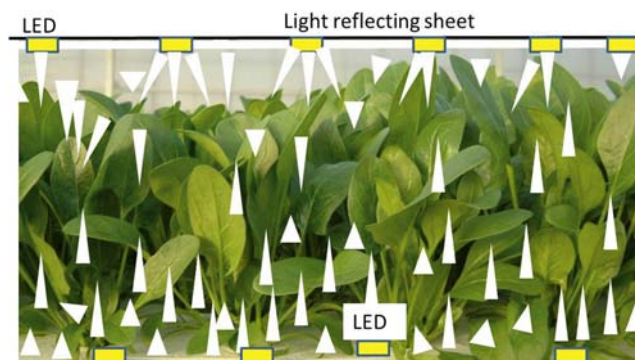


FIGURE 32.1

Diagram showing the concept of upward lighting using LEDs placed on the culture panels. In the PFAL, upward light which is not absorbed by the lower leaves is absorbed by the upper leaves or reflected back downward to the plant community by the light reflector placed above the plant canopy, to minimize the loss of upward light energy emitted from the LEDs.

than red and green photons, because almost all red and blue light photons are absorbed by the upper leaves, and thus are neither transmitted to the lower leaves nor reflected upward (Fig. 32.2; Kozai, 2012).

Owing to the recent widespread application of green LEDs to traffic signals, etc. and of white LEDs for office and home lighting, the cost performance of green and white LEDs has improved considerably, and so green and white LEDs with 25%–40% green light could be useful in the densely populated plant community in a PFAL. Recent studies indicate different effects of green light on plant growth and development (e.g., Kim et al., 2004; Johkan et al., 2012).

32.2.3 Layouts of LEDs

An LED lamp consists of many LED chips (around 0.3 mm square, 0.10–0.3 mm thick) and an LED chip consists of many LED elements. In addition to photosynthetic photon emission efficiency, spectral distribution and PPFD at the plant canopy level, and the layout of LED chips in an LED lamp (a tube like a fluorescent tube or a plate of different sizes), the following are important considerations when designing LED lamps and lighting systems using LEDs: (1) optical/chemical properties and 3-D shape of the plastic material cover, (2) enclosed fluorescent substances and directivity of photon emission, and (3) heat release function. The array design of LEDs affects the distribution of 2-D light quality on a leaf on a scale of 0.1 mm (Kozai et al., 2016). This microscale uneven distribution may cause edema of leaves (Mori and Takatsuji, 2013). Lighting system technology using LEDs for PFALs is still at the initial stage and much progress is expected to be made.

32.3 Breeding and seed propagation

32.3.1 Vegetables suited to PFALs

The most important genetic characteristic of field-grown and greenhouse-grown crops is their tolerance to diseases caused by pathogens, insects, and environmental stresses such as high/low temperatures, dry/wet soil/air, salt, toxic heavy metal accumulation, macro/micronutrient deficiency/excess, etc.

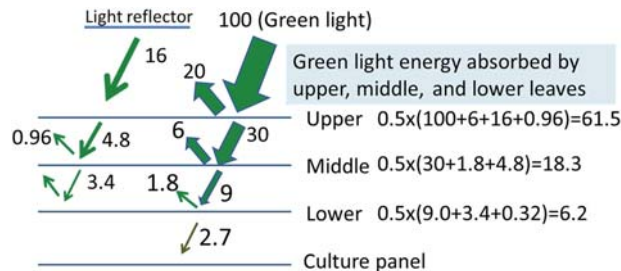


FIGURE 32.2

Schematic diagram showing the percentages of green light energy transmitted and reflected by upper, middle, and lower horizontal green leaves. Total green light energy absorbed by upper, middle, and lower leaves is also given. Red and blue light energy is absorbed by the upper leaf, and the middle and lower leaves receive almost no red or blue light energy. It is assumed that the percentages of reflection, transmission, and absorption of a horizontal leaf for green light energy are 20%, 30%, and 50%, respectively.

Growers will not want to commercially grow any crop that does not have tolerance to diseases or environmental stresses, even if the crop provides a high yield and high quality under narrowly specified conditions. Such high-yield, high-quality crops with little tolerance are suitable for growing in a PFAL, because plants grown in a PFAL need little tolerance to any disease caused by airborne pathogens or to environmental stresses (although it may be difficult to eliminate all pathogens in culture beds with nutrient solution).

Most breeders and breeding scientists may not imagine that they could breed a new cultivar showing a high growth rate and high quality just by removing the genes related to tolerance from a crop. However, such an “impractical” breeding approach has never been tried, and could lead to a new field of breeding and genetics. On the other hand, in the long history of crop breeding many breeding trials focusing on high-yield, high-quality crops have failed because of low tolerance to disease and/or environmental stress. Such breeding approaches could be used for production in PFALs (Kozai, 2018).

32.3.2 Seed propagation and breeding using PFALs

Commercial seed propagation is currently conducted once a year mainly in highlands in developing countries where the climate is often favorable for seed propagation, labor cost is relatively low, and pollination with unexpected plants can be avoided. However, the climate and weather in such areas are becoming increasingly changeable, labor costs are rising, and social infrastructure is sometimes unstable.

Many annual plant species can flower and pollinate within a few months after flower bud development. The success of flower bud formation, flowering, and pollination is largely influenced by the environment, especially light (photoperiod, quality, and intensity) and temperature. Therefore, the seeds of many annual plant species could be obtained three or four times a year in a PFAL by controlling the environment optimally for seed propagation. This method could be used for seed propagation and breeding of annual herbaceous plants. Or, seeding could be conducted every day or every week and plants with seeds could be harvested daily or weekly starting around 3 months later.

32.3.3 Medicinal plants

In recent years, more people have been demanding natural medicines, cosmetics, supplements, food additives, etc. In general, existing efforts to breed medicinal plants are not as advanced as those for horticultural and agricultural crops. Genetic traits of a certain species or variety are often diverse in a plant community, with wide variations in concentrations of medicinal components (secondary metabolites). In fact, many commercially used medicinal plants are still wild and harvested in their natural habitat, although some are selected for better genetic traits by visual observation by growers and then cultivated. In other words, most medicinal plants are not bred based on modern science such as molecular biology. This is one of the reasons why vegetative propagation of an elite mother plant, which is costly, is predominant over its reproductive seed propagation.

Concentrations and yields of medicinal components are largely affected by the environment. It is also difficult to obtain high-quality medicinal plants with high yields every year. On the other hand, the commercial value of medicinal plants per unit dry weight is much higher than that of leaf vegetables. Thus, if we can breed a high-quality, high-yield medicinal plant, register it as a new cultivar, and grow it under a controlled environment, it may be a good business opportunity.

In the case of medicinal plants, it is essential to grow them at a fast growth rate until near the end of the cultivation cycle, and then provide environmental stresses several days before harvest to sharply enhance the production of medicinal components. Note that it is possible to use both the aerial and root parts of traditional root medicinal plants such as wasabi and *Angelica sinensis*, when grown in PFALs.

32.4 Cultivation

32.4.1 Culture system with restricted root mass

The major function of plant roots is absorption of water, inorganic fertilizer, and dissolved oxygen. Other minor functions of roots include: (1) supporting the aerial part of the plant, (2) symbiosis with microorganisms, (3) barrier to infection by pathogens, (4) production of phytohormones such as cytokinin, and (5) leaching of organic acids to the root zone.

In a PFAL, electric energy is consumed to produce the plants, including roots. Thus, if the roots are not salable, the root mass must be minimized provided that doing so does not affect the growth of the aerial part.

In culture beds, plant roots require increasing amounts of water, fertilizer, and dissolved oxygen as the aerial parts of the plants grow. Thus, the flow rate and/or strength of nutrient solution must be increased as the plants grow. On the other hand, the flow rate of nutrient solution around the roots tends to decrease as the roots grow, due to the increase in resistance to the flow of nutrient solution in the culture beds. Considering this trade-off, a new culture bed with a solution circulation system which does not slow down the flow rate around the roots needs to be developed to promote the growth rate of the aerial parts of plants with minimum root mass.

32.4.2 Ever-flowering berry and fruit vegetable production in PFALs

Year-round production of strawberry fruit using ever-flowering cultivars and cherry and mini tomato plants in a PFAL is attracting much research interest and could be a global business opportunity. This business was started by a Japanese company in 2013, and many more groups in the world have been conducting experimental research on this subject.

Propagation and transplant production of blueberry plants have already been commercialized in North America (Chapter 22, Section 5). [Aung et al. \(2014\)](#) confirmed that continuous blueberry (*Vaccinium* spp.) production is possible throughout the year, including the off-season, through a combination of an open field, plastic houses/glasshouses, and controlled environment rooms with artificial lighting. Blueberry plants could be flowered year round and thus year-round production of blueberry fruits made possible ([Ogiwara and Arie, 2010](#)). Likewise, plants of raspberry, blackberry, etc. may be flowered and their fruits may be produced year round in PFALs.

32.5 PFALs with solar cells

Why are PFALs needed in addition to greenhouses with free solar energy to grow leafy vegetables? To answer this frequently asked question, we must consider three points: (1) there are large differences in light energy use efficiency (LUE) among PFAL, greenhouse, and open field, (2) the availability of solar energy largely depends on the time of day, weather, season, and location, and (3) the efficient use of

free solar energy in a greenhouse is costly because other environmental factors need to be controlled. Answers to points 1 and 2 have already been described in Chapters 3 and 2, respectively. The answer to point three, which is related to the answer to point two, is given here.

In an open field, it is difficult to use solar energy efficiently to grow plants in winter because the temperature is often too low, photosynthetically active radiation (PAR) flux is also often too low, and/or day length is much shorter than in summer. In order to use free solar energy efficiently during the cold winter in a greenhouse, the greenhouse must be heated, which is costly. To reduce the heating cost, a thermal screen needs to be installed, which incurs its own cost. To improve the yield and quality of crops in winter, the additional cost of installing a supplemental lighting system may be needed, while in the hot summer, costs are incurred for ventilation, shading, and/or evaporative cooling. If the greenhouse is simply left empty in winter and/or summer, the annual depreciation cost is high. In short, the insufficiency, excess, and uncontrollability of external solar energy are major factors limiting the economic profitability of plant production. This limitation is one of the reasons why leafy greens can be produced commercially in PFALs in very cold and very hot regions, even though PFALs consume much electricity.

Is it feasible to use solar energy for PFAL operation by generating electricity using photovoltaic (PV) cells? Intuitively, it seems unreasonable to use solar energy to generate electrical energy by PV cells, store the surplus in a battery, and then convert it to artificial light energy using LEDs to grow plants in the PFAL.

The percent conversions from solar radiation energy to chemical energy fixed in plants in a PFAL, a greenhouse heated in winter, and an open field can be estimated as follows. The percent conversion of PV cells from solar to electric energy is 20%–40% at most, while that of LEDs from electric to PAR is 30%–40% at most, and the percent conversion of PAR to chemical energy fixed in plants is 2%–4%. Multiplying all these factors together, the light use efficiency or percent conversion from solar energy to chemical energy is 0.12% ($0.2 \times 0.3 \times 0.02 \times 100$) to 0.64% ($0.4 \times 0.4 \times 0.04 \times 100$) at most.

On the other hand, the percent PAR to solar radiation energy is no more than 50%, and the annual average percent conversion from PAR to chemical energy in useable parts of plants is roughly estimated to be in the order of 0.10% in an open field and 1.0%–1.7% in a heated greenhouse (Kozai, 2013). Thus, the overall percent conversion from solar energy to chemical energy in useable plants is roughly 0.05% ($= 0.5 \times 0.001$) in open fields and 0.5%–0.85% (0.5×0.01 – 0.5×0.017) in a greenhouse. Therefore, these percentages in a PFAL and a greenhouse are not significantly different. Thus, it is too early to conclude that the use of solar energy using PV cells for PFAL is not feasible at all, even in arid and/or hot regions. The use of wind and geothermal energy in cold regions for PFAL with PV cells is also an interesting challenge. Note that the yield per unit land area is around 10 times and 100 times higher in a PFAL than in a greenhouse and open field, respectively.

Other challenging issues in PFAL R&D include: (1) the design and construction of an innovative building structure with facilities, (2) data mining using big data, (3) developing self-taught educational programs, (4) PFAL for farming on the moon, (5) international guidelines for the design, measurement, control, and management of PFAL, (6) developing an optimal environmental control system using minimum resources, (7) introducing molecular biology for breeding and solving physiological disorders of plants such as tipburn, (8) flexible automation of handling plants and supplies, and of cleaning the culture room, (9) creating new markets for PFAL-grown plants such as head-forming leafy vegetables harvested before heading, mini-carrots, mini-radishes, etc. with tasty leaves/shoots, and mineral-rich leafy greens, (10) service design of PFAL, (11) PFAL connected with other biological

and/or abiotic systems, (12) improving concentration and composition of functional components by environmental control, (13) breeding of dwarf plants suited to PFAL, and (14) development of phenotyping units (Kozai, 2018).

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Conclusions: resource-saving and resource-consuming characteristics of PFALs

33

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This chapter summarizes the resource-saving and resource-consuming characteristics of plant factories with artificial lighting (PFALs) as conclusions, since resources are the most important factor that determines the opportunities and challenges of PFALs, which consist of a thermally well-insulated and highly airtight structure containing multiple tiers with lighting and hydroponic units, CO₂ supply unit, air conditioners (or heat pumps), and control unit.

33.1 Roles of PFALs in urban areas

In addition to food production, PFALs as one form of agriculture play environmental, social, and cultural roles, as described in Chapter 2. PFALs are expected to become a key component in urban areas to help alleviate the following local and global issues:

- (1) Climate change (global warming), pest insects, and natural disasters (extreme wind, rain, flood, drought, etc.), and resultant vulnerabilities of crop yield and quality.
- (2) Increasing urban population.
- (3) Increasing demands for local production for local consumption to improve food security and safety.
- (4) Increasing demands for fresh food, nutritious food, functional food for health care and/or higher quality of life.
- (5) Increasing shortages and/or prices of water for irrigation and fossil fuels.
- (6) Decreasing population involved in agriculture due to aging of farmers.
- (7) Decreasing arable land area due to urbanization, soil contamination, and salt accumulation at soil surface, etc.
- (8) Decreasing opportunities for growing plants or producing foods by people living in urban areas.

33.2 Benefits of producing fresh vegetables using PFALs in urban areas

The benefits of producing fresh vegetables using PFALs in urban areas include:

- (1) Compared with field agriculture, over 100 times higher annual productivity per unit land area regardless of weather and season, by the use of multiple tiers, optimal environmental control,

minimum loss of plants to pest insects, etc. A large land area is not required for producing fresh foods.

- (2) PFALs can be built in shaded and/or unused areas such as an empty space in a building, and even the basement, because neither soil nor sunlight is needed.
- (3) The distance between production and consumption sites is minimized, thus reducing fuel consumption, CO₂ emissions, and traffic for food transportation.
- (4) Citizens can enjoy fresh food at lower prices.
- (5) Losses of fresh produce and/or fuel for cooling the produce during transportation are minimized.
- (6) Safe, enjoyable, and light-work job opportunities under comfortable environments are created for a wide range of people including elderly and handicapped persons.
- (7) Waste water, vegetable waste, and CO₂ produced in urban areas can be reused, after proper processing, as essential resources (water, CO₂, and fertilizer) for growing plants in PFALs. Waste heat energy can be used for heating greenhouses in winter and for other purposes.
- (8) The PFAL can be combined with aquaculture, mushroom culture, and fermentation systems for mutual efficient use of their respective wastes as resources.
- (9) Surplus electricity supply at nighttime compared with daytime can be used.

Other benefits of PFALs are described in [Kozai \(2018\)](#).

33.3 Resource-saving characteristics of PFALs

Compared with a greenhouse, PFALs can greatly reduce the consumption of resources other than electricity for high-quality plant production. The percentages of resources saved and improvement in produce quality and yield in a PFAL compared with a greenhouse are as follows:

- (1) 100% reduction in pesticide application by keeping the culture room clean and free from pest insects.
- (2) 95% reduction in water consumption by recycling water vapor that is transpired by plant leaves and condensed into liquid water at the cooling panels of air conditioners.
- (3) 90% reduction in land area compared with greenhouse thanks to a more than 10 times increase in annual productivity per unit land area (over 100 times increase in annual productivity compared to an open field).
- (4) 90% reduction in variation of yield and quality by accurate and optimal environmental control regardless of weather and season.
- (5) 50% reduction in fertilizer consumption by recycling with little drainage of circulating nutrient solution.
- (6) 50%–70% reduction in labor hours per unit yield by optimal layout of culture systems, organized operations, automation, and fewer physiological disorders of plants.
- (7) 10%–30% reduction in plant residue by less loss caused by physical, chemical, and biological damage of produce.

The experimental evidence and theoretical explanations for these percentages are given in relevant chapters of this book. However, more rigid experimental evidence and deeper theoretical considerations are needed for more widespread use of PFALs.

33.4 Possible reductions in electricity consumption and initial investment

The key tasks for the next-generation PFALs are: (1) to reduce electricity consumption for lighting and air conditioning per kg of produce by improving the lighting system, etc., (2) to reduce the initial resources and financial investment, and (3) to generate electrical energy from solar power, wind power, biomass energy, and geothermal energy, and use the electricity most efficiently with use of batteries.

33.5 Electricity consumption

At present, approximately 7–10 kWh (25–36 MJ) of electrical energy are consumed to produce 1 kg of salable fresh lettuce heads. This electricity consumption can be reduced by 50% (4–5 kWh fresh weight) in the near future by (Kozai et al. 2016):

- (1) Using LEDs with optimal light quality, lighting cycle, and lighting schedule,
- (2) Using a well-designed lighting system with reflectors to maximize the ratio of light energy received by plant leaves to the light energy emitted from light sources and providing uniform lighting to all leaf surfaces,
- (3) Optimally controlling temperature, CO₂ concentration, and nutrient supply to maximize plant photosynthesis, growth, and dry matter production for a given consumption of electrical energy,
- (4) Optimizing the transplanting schedule or automatic spacing to maximize the planting density on the culture panels, and
- (5) Maximizing the percent salable parts of plants (minimizing plant residue).

These statements are based on electrical energy conversion to carbohydrates. The economic value per kilogram of produce or per kilowatt-hour (joule) of electrical energy can be further improved by environmental control and appropriate choice of cultivars for production of desired secondary metabolites of this book.

33.6 Initial resource investment

Cement and iron are the two major materials whose consumption should be greatly reduced in PFAL construction, because a large amount of energy is required and a large amount of CO₂ is emitted during their production and the construction of a PFAL. Wood may be a possible alternative material for parts of the PFAL.

33.7 Increasing the productivity and quality

Annual productivity of leafy vegetables per unit land area with existing PFALs is over 100 times that in open fields. Next-generation PFALs will offer 200 times greater annual productivity, as well as higher economic value thanks to higher quality. Resource and monetary productivities of PFALs in Japan are discussed in detail by Kozai et al. (2019).

33.8 Dealing with power cuts

A power cut caused by unpredicted electric failure for about 10 h in a PFAL does not significantly affect plant growth. In general, plants in a PFAL receive 15–16 h of light daily. If a light period is only 10 h due to a power cut, the following light period can be extended to 20 h or so.

Also, since PFALs are thermally well insulated and highly airtight, the air temperature in the culture room changes very slowly with the air temperature outside if all the lamps and air conditioners are off. Therefore, plant growth is hardly affected for a half day or so, even if the outside temperature is extremely high or low. Nevertheless, a back-up system should be installed in the PFAL to operate the pump that circulates the nutrient solution.

33.9 Challenges

Challenging issues regarding the efficiency of resource use in a PFAL, as described in Chapter 32, include:

- (1) Improving the lighting system: (a) upward lighting, (b) use of green LEDs, and (c) layout of LED chips in an LED lamp.
- (2) Breeding and seed propagation: (a) selection and breeding of vegetables suited to PFAL, (b) seed propagation using the PFAL, and (c) breeding using the PFAL.
- (3) Selection, breeding, and environmental control for efficient secondary metabolite production of medicinal and/or functional plants.
- (4) Production of pharmaceuticals by transient expression methods.
- (5) Development of a new cultivation system with restricted root mass to increase the weight ratio of salable part to total plant weight.
- (6) Ever-flowering strawberry, blueberry, and other berry production in PFALs.
- (7) PFALs with solar cells with or without batteries networked with other natural energy systems.
- (8) Production of raw materials for processed foods such as paste, sauce, pickled vegetables, juice, cosmetics, aromas, etc.
- (9) Integrating PFALs into ecological urban planning and management.
- (10) Micro-, mini-, and small PFALs for education, self-learning, and as a hobby.
- (11) Biochemical and molecular biological analyses of the environmental and genetic effects on functional components and physiological phenomena, and their application for breeding and environmental control.
- (12) Data mining using big data obtained from the PFAL system.
- (13) Introducing information and communication technology into the PFAL.
- (14) Development of a phenotyping unit for noninvasive measurement of plant traits ([Kozai, 2018](#)).

There may be many other issues to tackle for conserving resources in a PFAL.

In order to improve the resilience and sustainability of society, more diverse plant production systems including open fields and greenhouses are required. The PFAL is one such plant production system.

This book has emphasized the usefulness of PFALs in urban areas. However, PFALs can also be useful in rural and local areas where electricity is supplied from renewable energy. PFALs can also be

used for various purposes where plants cannot be grown due to conditions such as harsh weather, shortage of water, and soil degradation, as long as electricity is available.

Finally, we must distinguish the technologies and costs of current PFALs from those of PFALs 5, 10, and 20 years later. Research, technology, business, and applications of PFALs have only just started and will progress rapidly, offering many opportunities as well as challenges. Recent advanced technologies such as artificial intelligence (AI), IoT (Internet of Things), bioinformatics, omics (metabolomics, proteomics, genomics, phenomics), robotics, computer network, and data warehouse will be introduced to develop the next-generation smart PFALs (Kozai, 2018).

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PLANT FACTORY

An Indoor Vertical Farming System for Efficient Quality Food Production

Optimize the increasingly viable agricultural alternative solution that allows food crops to be grown in indoor vertical farming systems using electric lights.

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Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production presents a comprehensive look at the implementation of plant factory (PF) practices to yield food crops for both improved food security and environmental sustainability. Now in its second edition, the book has been fully revised and updated to include the latest advances in PF technologies. Edited and authored by leading experts in PF and controlled environment agriculture (CEA), the book is divided into four sections, each focused on a key element of successful PF: Section 1: Overview and Concept of Closed Plant Production Systems (CPPS); Section 2: Basics of Physics and Physiology—Environments and Their Effects; Section 3: System Design, Construction, Cultivation, and Management; and Section 4: Plant Factories in Operation.

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