Edited by

Toyoki Kozai, Genhua Niu,
and Joseph Masabni

Plant Factory

Basics, Applications and Advances

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Contributors

Yumiko Amagai Center for Environment, Health and Field Sciences, Chiba University, Kashiwa, Chiba, Japan

Bruce Bugbee Utah State University, Logan, UT, United States

Hiroshi Ezura Faculty of Life and Environmental Sciences, University of Tsukuba, Tsukuba, Ibaraki, Japan; Tsukuba-Plant Innovation Research Center, University of Tsukuba, Tsukuba, Ibaraki, Japan

Kazuhiro Fujiwara Graduate School of Agricultural and Life Sciences, The University of Tokyo, Tokyo, Japan

Celina Gómez Environmental Horticulture Department, University of Florida, Gainesville, FL, United States

Eri Hayashi Japan Plant Factory Association, Kashiwa, Chiba, Japan

Ricardo Hernández Department of Horticultural Sciences, College of Agriculture and Life Sciences, North Carolina State University, Raleigh, NC, United States

Kyoko Hiwasa-Tanase Faculty of Life and Environmental Sciences, University of Tsukuba, Tsukuba, Ibaraki, Japan; Tsukuba-Plant Innovation Research Center, University of Tsukuba, Tsukuba, Ibaraki, Japan

Yasuomi Ibaraki Yamaguchi Universiy, Yamaguchi City, Japan

Harumi Ikei Center for Environment, Health and Field Sciences, Chiba University, Chiba, Japan

Murat Kacira Department of Biosystems Engineering, The University of Arizona, Tucson, AZ, United States

Katashi Kai Shinnippou Ltd., Shizuoka, Japan

Kazuhisa Kato Graduate School of Agricultural Science, Tohoku University, Sendai, Miyagi, Japan

Nathan Kelly Department of Horticulture, Michigan State University, East Lansing, MI, United States

Volkmar Keuter Department Photonics and Environment, Fraunhofer Institute for Environmental, Safety, and Energy Technologies UMSICHT, Oberhausen, Germany

Masao Kikuchi Center for Environment, Health and Field Sciences, Chiba University, Kashiwa, Chiba, Japan

Toyoki Kozai Japan Plant Factory Association, Kashiwa, Chiba, Japan

Paul Kusuma Utah State University, Logan, UT, United States

Tisha Livingston 80 Acres Farms, Hamilton, OH, United States

Na Lu Center for Environment, Health and Field Sciences, Chiba University, Kashiwa, Chiba, Japan

Toru Maruo Japan Plant Factory Association, Kashiwa, Chiba, Japan

Joseph Masabni Texas A&M AgriLife Extension Service, Dallas, TX, United States

Genhua Niu Texas A&M AgriLife Research, Texas A&M University, Dallas, TX, United States

Yujin Park College of Integrative Sciences and Arts, Arizona State University, Mesa, AZ, United States

P. Morgan Pattison Solid State Lighting Services, Inc., Johnson City, TN, United States

H. Christopher Peterson Michigan State University, East Lansing, MI, United States

Erik S. Runkle Department of Horticulture, Michigan State University, East Lansing, MI, United States

Joseph Seong Michigan State University, East Lansing, MI, United States

Yutaka Shinohara Japan Plant Factory Association, Kashiwa, Chiba, Japan

Michiko Takagaki Center for Environment, Health and Field Sciences, Chiba University, Kashiwa, Chiba, Japan

Kaz Uraisami Marginal LLC, Tokyo, Japan

Simone Valle de Souza Michigan State University, East Lansing, MI, United States

Viktorija Vaštakaitė-Kairienė Institute of Horticulture, Lithuanian Research Centre for Agriculture and Forestry, Babtai, Lithuania

Victor Verlage 80 Acres Farms, Hamilton, OH, United States

Mike Zelkind 80 Acres Farms, Hamilton, OH, United States

Ying Zhang Department of Agricultural and Biological Engineering, University of Florida, Gainesville, FL, United States

Shuyang Zhen Texas A&M University, College Station, TX, United States

Preface

Plant factory with artificial lighting (PFAL) or indoor vertical farming, a technology-based innovative approach to sustainable food production, is capturing the interests of people with all levels of experience and expertise around the globe. Many universities have created and expanded their research and teaching programs in controlled environment agriculture. The number of plant factories, large and small with varying degrees of productivity and profitability, is also increasing. In the past five years, several technical books on plant factories have been published, including those authored by the editors of this book. However, PFAL technologies are evolving rapidly with the advances in many related fields such as lighting technology, photobiology, plant nutrition, breeding, and environmental control engineering. PFAL applications are expanding to a wider range of vegetable, ornamental, and medicinal crops. All these new developments have encouraged us to write another book that discusses the latest advancements and new topics and covers the basics of PFAL.

This book consists of four parts: introduction, basics, applications, and advanced research. Part I summarizes the role and characteristics of PFALs and its potential contribution to the United Nation's sustainable development goals and beyond. Part II covers the technical basics from lighting terminology, light-emitting diode performance and efficacy, to cultural methods such as hydroponics and aquaponics. Part III discusses aspects of PFAL application such as optimization of crop productivity, economics and profitability, and business models. Part IV introduces the latest advances in research in PFAL.

The target audience for this book are researchers, engineers, students, educators, businesspeople, and policymakers in the field of horticulture, food production, and urban agriculture. We hope this book will provide a good reference for PFAL technology and science, inspire new business opportunities, and advance technological developments that improve the productivity and profitability of PFALs.

We are deeply indebted to all the authors for their timely contribution. We specially thank Ms. Tokuko Takano for her tireless assistance.

Genhua Niu,
Toyoki Kozai,
and Joseph Masabni

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PART I

Introduction

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CHAPTER

1

Introduction: why plant factories with artificial lighting are necessary

Toyoki Kozai[1], *Genhua Niu*[2] *and Joseph Masabni*[3]

[1]**Japan Plant Factory Association, Kashiwa, Chiba, Japan;** [2]**Texas A&M AgriLife Research, Texas A&M University, Dallas, TX, United States;** [3]**Texas A&M AgriLife Extension Service, Dallas, TX, United States**

1.1 Introduction

Today, we face global as well as local issues in areas such as climate systems, biodiversity, land utilization, and shortages of phosphorus (P) and nitrogen (N) reserves, all of which are interrelated and affect the sustainability of our planet (Rockstrom and Klum, 2015, Fig. 1.1). Excessive use of P and N as chemical fertilizers in agriculture and excessive wastewater emissions in urban areas have caused and continue to cause eutrophication in rivers and lakes, thus resulting in environmental pollution in surrounding areas and, at the same time, causing a shortage of phosphate ore reserves in mines for future use in agriculture.

According to Rockstrom and Klum (2015), biodiversity and P/N flows are already beyond the high-risk zone with regard to planetary boundaries of the Earth's systems, and land utilization and climate systems are also approaching the high-risk zone. Since major countermeasures to address these issues are also interrelated, they need to be planned and implemented concurrently, step by step, and from various aspects on different scales.

Solving the above four issues concurrently to improve the resilience of the planet's sustainability through "transformation of the economic and social systems" with respect to food, energy, urban, and production and consumption systems (Fig. 1.2) is also in line with the principles of earth stewardship of the global commons (Chapin et al., 2011; The World in 2050, 2019).

We must construct and manage a sustainable food system bearing in mind a future that will be characterized by the following: (1) a significant increase in the urban population (about eight billion or 80% of the world's population by 2050) in tandem with increasing demand for higher food quality and security; (2) increases in social, political, economic,

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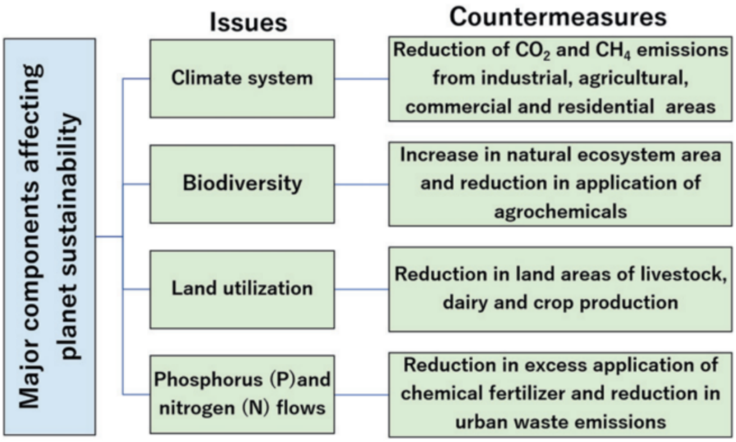

FIGURE 1.1 Planetary boundaries in the zone of increasing risk (climate change and land use change) and beyond the zone of high risk (biodiversity and P/N flows). *Adopted from Rockstrom, J., Klum, M., 2015. Big World Small Planet. Yale University Press, 206.*

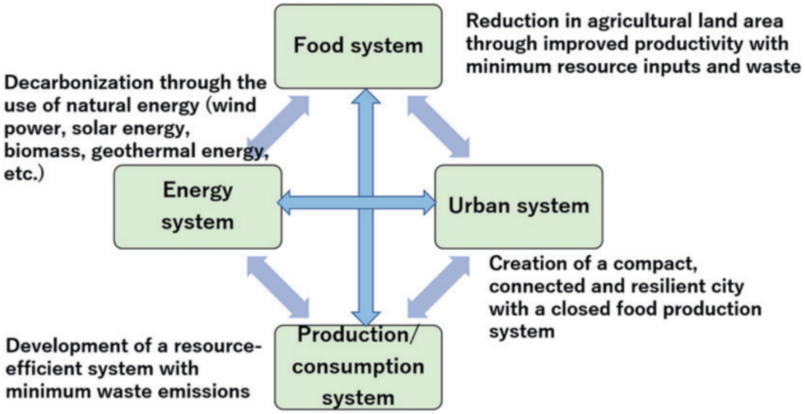

FIGURE 1.2 Social and economic systems to be transformed to improve the resilience of sustainability of our planet. Four interrelated global as well as local issues to be solved under global commons stewardship. *Adopted from Chapin III, F.S., S.T.A. Pickett, Power, M.E., Jackson, R.B., Carter, D.M., Duke, C., 2011). Earth stewardship: a strategy for social—ecological transformation to reverse planetary degradation. J. Environ. Stud. Sci. 1, 44—53.*

and pandemic risks in areas such as international transportation and the trade of safe, secure food; (3) a contraction in the agricultural population due to the aging of farmers and growers, and decreases in arable land area, availability of water for irrigation, and P and K (potassium) fertilizer; and (4) climate change events such as floods, droughts, typhoons/hurricanes, and high temperatures, resulting in crop damage.

Consequently, there is a pressing need for sustainable intensification of agricultural production on a global scale; in other words, agricultural processes or systems where yields are increased without adverse environmental impact and without the conversion of additional nonagricultural land (Royal Society, 2009). It is becoming increasingly clear that the so-called Digital Revolution (DR) is becoming a key driving force in sustainable intensification and system transformation with respect to a sustainable food system. A host of recent technologies is also advancing the DR such as virtual and augmented reality, 3D printing, artificial intelligence (AI), the Internet of Things (IoT), the fifth generation wireless network, cloud computing, robots, smartphones with superior cameras, global positioning systems, bioinformatics, and various kinds of application software for smartphones and their peripheral devices. The DR will radically alter all dimensions of global and regional society and economies and will therefore change the interpretation of the sustainability paradigm itself (The World in 2050, 2019) particularly since the outbreak of the Covid-19 (coronavirus) pandemic in 2020.

1.2 Global land use and environmental impact of livestock

1.2.1 Global land use

As shown in Table 1.1, 29% of the Earth's surface is covered by land, and about 71% of that land area is habitable. Approximately half of all habitable land is used for agriculture. About 77% percent of the global agricultural land area is used for livestock, including pastures for grazing and land for growing animal feed. Only about 37% of habitable land is covered by forests, 11% by shrubs and grasslands, and 1% by fresh water. The remaining 1% or 1.5 million km^2 is comprised of urban and built-up areas which include cities, towns, villages, roads, and other human infrastructure (Richie, 2019). In 2050, 80% of the global population (nearly eight billion people) will live in urban areas, which account for only 1% of the habitable land area on Earth.

The expansion of agricultural land has been one of humanity's largest impacts on the environment, and one of the greatest pressures on biodiversity (Richie, 2019). Furthermore, agricultural land/soil is often degraded by extreme weather and adverse land management by humans. The processes of agricultural land degradation include erosion, organic matter

TABLE 1.1 Global land use for food production (Richie, 2019; Richie and Roser, 2020; Our World in Data https://ourworldindata.org/) (All the percentages are approximate values).

	Use by % and area		
Category	**(%)**	**10^6 km^2**	**Other uses (%)**
Earth's surface (514 10^6 km^2)	29% land	149	71% ocean
Land surface	71% habitable	104	10% glaciers, 19% barren land (deserts, dry salt flats, beaches, sand dunes, and exposed rocks)
Habitable land	50% agriculture	51	37% forest, 11% shrub, 1% freshwater, and 1% urban/built-up land
Agricultural land	77% livestock (meat and dairy)	40	23% crops excluding feed crops

decline, salinization, soil diversity loss, contamination, flooding, landslides, and sealing (Xydis et al., 2020).

1.2.2 Environmental impact of livestock and countermeasures

To produce 18% of calories and 37% of proteins needed in our diet from meat and dairy, 77% of agricultural land is needed for use by livestock and 23% for crops excluding feed crops. However, it should also be noted that 57% of the land used for feed production is not suitable for food production (Mottet et al., 2017) mainly due to unfavorable soil and climate. In the United States, 56% of water drawn from rivers or wells is used for livestock (Poore and Nemeeek, 2018). Moreover, 58% of greenhouse gases (GHGs) and 57% and 56% of water and air pollution, respectively, are attributable to the livestock industry.

From 1970 to 2016, global meat production increased nearly fourfold, with a production of nearly 320 million tons annually, and this growth is set to continue to increase in tandem with global population and economic growth unless people make considerable dietary changes. Dry matter feed required to produce 1 kg of edible parts of beef, lamb/mutton, pork, and poultry is 25, 15, 6.4, and 3.3 kg, respectively, and (Mottet et al., 2017) feed required to produce 1 kg of eggs and milk is 2.3 and 0.7 kg, respectively (Alexander et al., 2016). This conversion efficiency from feed to edible meat can be improved by better livestock management. For example, to produce 1 kg of boneless meat requires 2.8 kg human-edible feed in ruminant systems and 3.2 kg in monogastric systems (Mottet et al., 2017). The three major feed materials of six billion tons of global feed (dry matter) in 2010 were grass and leaves (46%), followed by crop residues such as straws, sugarcane (19%), and human-edible grains (13%) (Mottet et al., 2017).

Reducing meat and dairy dietary intake, thus reducing the land area and feed consumption required for livestock, is the most effective way of reducing the environmental impact on Earth (Carrington, 2018). Improving feed-meat/milk/egg conversion efficiency is another effective way of reducing the environmental impact on Earth.

A simple, direct countermeasure for reducing the land area for livestock is the substitution of meat with plant-based alternatives. Plant-derived meat or plant meat is one such alternative and is similar to meat in appearance and taste. In terms of calorie production and protein for humans, it requires less land area, freshwater withdrawals, and P/N fertilizer, and causes lower emissions of GHGs and water and air pollutants. Therefore, a significant percentage of farmland can be restored to forests and natural habitats. In addition to plant-derived foods, insect-derived foods will become another important option for providing protein as food for humans and feed for livestock and fish (van Huis, 2013).

1.3 Scope and organization of this book

In view of the statistical facts and the opinion of qualified researchers on trends in global land use and the environmental impact of agriculture and changes in agricultural and urban population described earlier, it is clear that we have to change the conventional food chain system and our dietary habits to make them more sustainable.

One of the options for making the food chain system more sustainable is the concept of the vertical farm (Despommier, 2010) and/or plant factory (Kozai et al., 2020). In fact, in the previous decade, a significant number of papers on vertical farms and plant factories have been published by researchers of various backgrounds in educational, research, and business.

1.3.1 Objective

The plant factory with artificial lighting (called PFAL hereafter) discussed in this book is one type of vertical farm as explained in Chapter 2. The objective of this book is to demonstrate the usefulness of PFALs in contributing to solve concurrently a number of issues relating to food, the environment, natural resources, and quality of life. In brief, the PFAL is considered to contribute to the following: (1) solving global and local issues relating to food, urban, energy, and production/consumption systems concurrently (Fig. 1.2); (2) achieving the Sustainable Development Goals (SDGs); and (3) adopting ESG (environmental, social, and corporate governance) criteria through sustainable intensification of plant production (SIPP) (The Royal Society, 2009, Fig. 1.3).

Bearing in mind the SIPP shown in Fig. 1.3, this book intends to stimulate and inspire readers to discover new research areas and business opportunities in regard to PFALs, based on an understanding of basic sciences, creative viewpoints, and innovative methodology. This book is neither a text that aims to cover all aspects of PFAL research and business nor a comprehensive literature review of PFALs. What it does cover are the benefits of PFALs, the challenges of the next generation of PFALs, and selected topics not discussed in detail in previous books on PFALs (Kozai et al., 2016, 2020; Kozai, 2018).

1.3.2 Organization of this book

This book consists of four sections: Introduction, Basics, Applications, and Advanced research. In Part 1, Chapter 2 examines the differences in meaning between the PFAL and

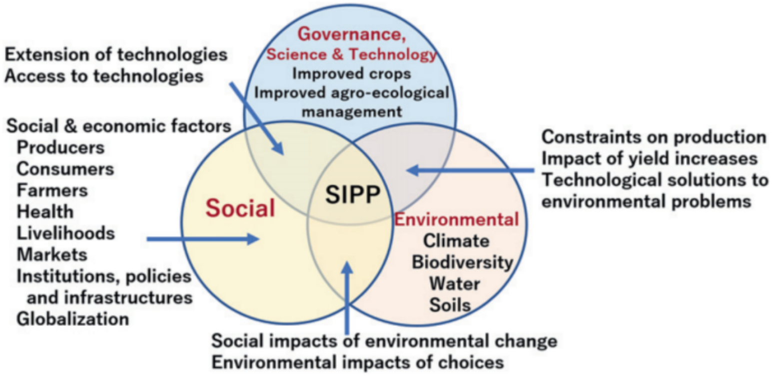

FIGURE 1.3 Sustainable intensification of plant production (SIPP) in relation to ESG (environmental, social, and corporate governance). *Adopted from The Royal Society. 2009. Reaping the Benefits: Science and the Sustainable Intensification of Global Agriculture. The Royal Society, London, 71.*

vertical farm or indoor farm, while Chapter 3 describes the role and characteristics of PFALs, and Chapter 4 discusses how PFALs can contribute to achieving the SDGs.

In Part 2, Chapters 5 and 6 explain basic technical terms and SI (System International) units and their relationship in regard to light and light sources. Chapter 7 describes the current and potential efficacy of light emitting diodes and Chapter 8 discusses resource use efficiency. Chapters 9 and 10 discuss hydroponics and aquaponics as essential components of indoor vertical farms, and Chapter 11 explores plant responses to environments.

In Part 3, Chapters 12 and 13 propose a definition of productivity and methods of optimizing the productivity of PFALs. Chapter 14 discusses the economics and profitability of PFALs, and Chapter 15 discusses their cost performance and presents some business models.

In Part 4, Chapters 16–23 discuss in detail a range of topics including the following: the optimal spectra of light for indoor plant growth, effects of light on plant nutrition and secondary metabolites, transplant production, environmental control, molecular breeding of tomato lines, production of strawberries, production of tomatoes, phenotyping, and a human-centered perspective on urban agriculture.

1.3.3 Benefits and challenges

The benefits of PFALs and challenges in achieving more sustainable PFALs are summarized below as the introductory part of this book. These topics are discussed in the chapters that follow.

1.3.3.1 Benefits of PFALs

(1) The land area usage of a PFAL with 10 tiers is reduced to about 1/20th that of conventional open field vegetable production, and the amount of water required for irrigation per kg of produce is reduced to 1/20th of that of greenhouse production. In addition, food loss and fuel consumption during transportation are reduced due to reduced food mileage.

(2) With PFALs, high-yield and high-quality produce with year-round production is possible everywhere in the world regardless of climate, weather, or soil fertility mainly due to the PFAL's high environmental traceability, controllability, and reproducibility.

(3) Pesticide-free, insect-free, and other contaminant-free PFAL-grown leaf vegetables with an extremely low population density of microorganisms are clean enough to be served as fresh salad without washing, and the produce shelf life is about twofold that of greenhouse-grown vegetables.

(4) Since the environment in the cultivation room is more or less the same everywhere in the world, the exchange of information via the Internet among PFAL users is easy and beneficial.

1.3.3.2 *Challenges in achieving more sustainable PFALs*

(1) The cost of electricity, which accounts for around 20% of production costs in Japan as of 2020, must be further reduced by generating all electricity from natural energy.
(2) The development of software for more efficient lighting systems, optimal environment control, user-friendly universally designed PFALs, online and onsite training courses for beginners and skilled workers, human centered PFALs, and modularized, scalable, and networked PFALs is essential.
(3) The integration of PFALs with other biological and engineering systems with appropriate use of advanced technologies such as AI and the IoT is necessary, taking into consideration the life cycle assessment of various types of PFALs (Kikuchi et al., 2018).
(4) The breeding of cultivars of leaf, fruit and head vegetables, and medicinal and flowering plants suited to PFALs is essential.

More detailed discussion regarding the challenges is provided in Chapter 3.

1.4 Conclusion

The PFAL is an emerging, yet still immature, technology. As a result, proven benefits are limited at present. Nevertheless, the number of PFALs that are generating economic profits has been increasing, particularly since around 2015. On the other hand, there are still a host of challenges to be tackled and solved to actualize the full potential and opportunities that PFALs offer in contributing to the achievement of the SDGs and urban sustainability.

To make full use of PFAL potential in urban areas, citizen science applying interdisciplinary and transdisciplinary approaches is essential (Grandison, 2020) as a means of raising awareness about PFALs, having them accepted, widely utilized, and continuously improved by all stakeholders including consumers, growers/farmers, PFAL employees, city planners, policy makers and business persons, and incorporating them into the everyday life of people everywhere.

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CHAPTER

2

Terms related to PFALs

Toyoki Kozai
Japan Plant Factory Association, Kashiwa, Chiba, Japan

2.1 Introduction

This chapter describes mainly the similarities and differences in meaning between "vertical farm," "plant factory," and "plant factory with artificial lighting (PFAL)." The terms "indoor farm" and "indoor vertical farm" are sometimes used interchangeably for vertical farm. All of the above terms are recently being increasingly used both as general terms as well as technical terms in research papers.

Nevertheless, there are no standard or clear definitions of these terms which distinguishes one from the other, so they are often used interchangeably, which occasionally leads to misunderstanding or confusion. Thus, establishing clear definitions of these terms and their relationships is warranted to avoid confusion. The author intends for this chapter to be a starting point in stimulating discussion of these terms to clarify their respective meanings for easier communication in the future.

The author believes that the definition of a vertical farm should take into consideration its structure, role, and function including its future integration with other biological facilities such as wastewater and plant residue processing facilities.

2.2 Vertical farm

2.2.1 Vertical farm versus vertical farming

Waldron (2019) pointed out the important difference in concepts between "a vertical farm" as a noun and "vertical farming" as an activity (or gerund). The discussion in this chapter takes up only the term "vertical farm," although the term and concept of vertical farming is important in the design and management of vertical farms.

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2.2.1.1 Vertical farms as an agricultural production system

2.2.1.1.1 Vertical farms in a broad sense

According to Al-Kodmany (2018), the term "vertical farm" was coined by G. E. Bailey (1915) who authored a book on geology entitled *Vertical Farming* describing the history and processes of the physical structure and substances of the agricultural land. The term had been popularized in an earlier book entitled *The Vertical Farm: Feeding the World in the 21st Century* by Dickson Despommier (2010), who described vertical farming as "the mass cultivation of plant and animal life for commercial purposes in skyscrapers." Since then, the term vertical farm has been used worldwide, particularly in North America and Europe. Banerjee and Adenauer (2014) referred to vertical farming as "a system of commercial farming whereby plants, animals, fungi, and other life forms are cultivated." In a review of vertical farming, Kalantari et al. (2017) also included aquaculture, livestock production, and waste management. It is only natural and logical that plants, animals, and other life forms would be produced in vertical farms since the term "farm" refers to an area of land and buildings for growing crops and rearing animals (Oxford Dictionary of English).

2.2.1.1.2 Key factors for classifying vertical farms

Fig. 2.1 shows the classification of vertical farms based on various key factors. The vertical farm can be further subclassified under the respective key factors.

Waldron (2019) proposed the following factors for considering the classification of vertical farms: (1) scale of production, (2) density/volume of production (high density vertical cultivation), (3) environmental controls (building integrated controlled environment farm and controlled environment agriculture), (4) layout (i.e., racking systems), (5) building type/structure (sky farming), and (6) location (urban farms).

2.2.1.1.3 Classification of vertical farms by produce type

Fig. 2.2 shows a classification of vertical farms by produce types, one of the key factors shown in Fig. 2.1. Vertical farms are classified into the following: (1) plant farms (vertical farms for plant production); (2) insect farms (Madau et al., 2020; Specht et al., 2019); (3) fish/shellfish farms (aquaculture system); (4) animal farms (chicken house, pig house, cow house, etc.); and (5) microorganism farms. In Fig. 2.2, two-spotted cricket (*Teleogryllus occipitalis*), field cricket (*Teleogryllus*), and black soldier fly (*Hermetia illucens*) are considered as feed for fish, shellfish, and livestock and as protein source (food) for humans among others.

The plant farm is subdivided into PFALs, which are defined in Section 3, and plant farms other than PFALs which are called "plant factory" (common noun) in this book. In Fig. 2.2, the word "vertical" is added as a prefix to each farm when it has an upright structure or occupies a tall building with many stories. For example, "vertical plant farm" in place of "plant farm."

The classification shown in Fig. 2.2 is based on the understanding that R&D and the industry of all types of vertical farms will continue to grow in the coming years. Therefore, clear definitions of basic terms common to all types of vertical farms will become increasingly important to avoid possible confusion. This will be especially so when plant farms, for example, are integrated with other types of vertical farms. Vertical farms can be classified based on various key factors other than produce type, as shown in Fig. 2.1.

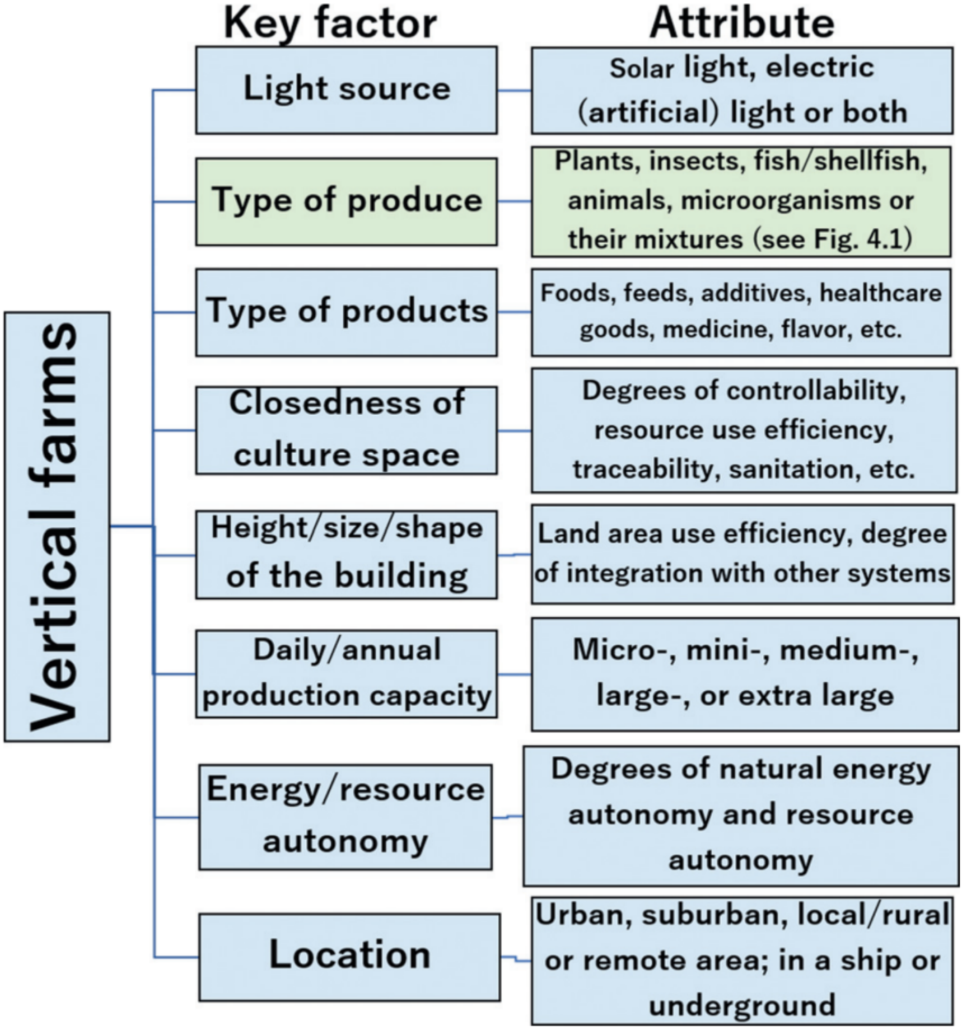

FIGURE 2.1 A classification of vertical farms by key factors.

2.2.1.2 Vertical farms in a narrow sense—a plant production system

In his review of vertical farms, Al-Kodmany (2018) simply described the various types of indoor plant production systems. Sharath Kumar et al. (2020) described the vertical farm as "a multitier indoor plant production system … independent of solar light and other outdoor conditions." This description also seems to be reasonable since, as of 2020, most existing facilities or buildings referred to as vertical farms exclusively cultivate plants as produce. In fact, many horticultural researchers in the United States and Europe understand vertical farming to be the production of crops (or plants) grown in completely enclosed environments with electric lamps as the sole source of light (i.e., no sunlight, based on the author's

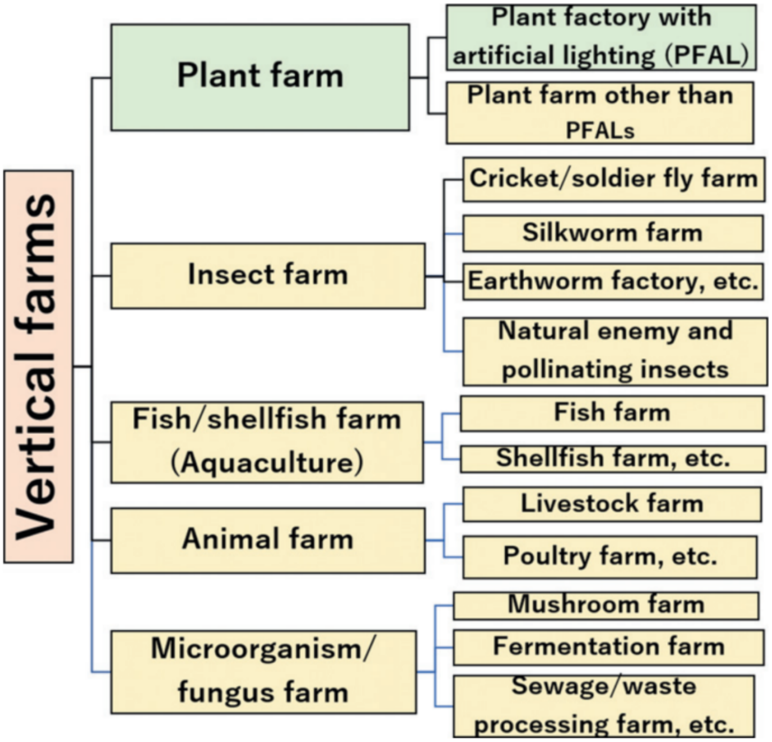

FIGURE 2.2 A classification of vertical farms by types of produce.

communication with E. Runkle). On the other hand, it might become difficult to refer to plant farming as vertical farming as other types of vertical farms such as vertical fish farms and vertical insect farms develop.

2.2.1.3 *Type of light source*

The description in the previous section on vertical farms raises another point for discussion: the light source. Rooftop greenhouses with or without supplemental electric lamp lighting and indoor plant production systems using both solar and lamp lighting are included in the vertical farms in many papers (e.g., Kalantari et al., 2017). In some cases, greenhouses built on the ground are included in indoor farms. Vertical farms graphically illustrated in Despommier (2010) include rooftop greenhouses and plant cultivation systems with full or partial use of solar light transmitted through glass windows on exterior walls. In fact, some existing vertical farms use both artificial and natural (solar) light (e.g., Gerner et al., 2011), although most existing vertical farms use light from electric lamps as the sole light source.

2.2.1.4 *Photosynthetically and physiologically active radiation*

The wavelength of solar radiation ranges from around 300 to 2500 nm at the peak wavelength of about 500 nm (end of blue-green). The solar radiation ranging from 800 to 2500 nm accounts for around 50% of total solar radiation energy and is called thermal radiation (i.e., physiologically nonactive radiation for plants and animals).

Photosynthetically active or photosynthetic radiation ranges from about 400 to 700 nm, and physiologically active radiation for plants ranges from about 300 to 800 nm, including ultraviolet (UV) radiation A and B (about 300–400 nm), photosynthetically active radiation, and far-red radiation (700–800 nm). Visible light for humans ranges between 380 and 740 nm. LED lamps used in PFALs/vertical farms emit physiologically active radiation with a very small amount of near-infrared and infrared radiation.

Radiation energy required for the photosynthetic growth of plants is much greater than that required for the photo-physiological reaction of plants such as photomorphogenesis, since photosynthesis is an energy conversion process, while photomorphogenesis is a signal conversion process. This is why electricity consumption for lighting is much greater in PFALs than in livestock/poultry houses and why the design and management of the lighting environment for plant production is considerably different from the design and management for animal production. The differences among photosynthetic radiation, photosynthetic photons, physiologically active radiation, and photons are described in Chapters 5, 6, 11 and 17.

2.2.1.5 The words "indoor," "closed," "factory," and 'farm'

The word "indoor" means "in a building or under cover," and the word "closed" means "surrounded by (side) walls," so that it is clear that all indoor farms, indoor vertical farms, and closed farms refer to farms that are closed or, at least, under cover. A factory is also understood to be a closed structure. On the other hand, the term "vertical farm" itself does not imply that it is closed. This is why the term "indoor vertical farm" is often used to indicate a closed vertical farm.

From a traditional point of view, the word "farm," particularly among older people, evokes images of rural landscape and perhaps even experiences from childhood. Many people thus associate the word "farm" with nature or natural, or not artificial. In this context, the word "farm" has a connotation that differs qualitatively from "factory" and "artificial."

2.2.1.6 The word "vertical"

The word "vertical" in vertical farm means "upright," and thus "vertical farm" refers to a high-rise or tall building (with many stories) or a skyscraper with plants and/or livestock growing inside, which is often associated with the words urban, modern, and/or high tech (Despommier, 2010). On the other hand, the term vertical farm is recently being used also to mean a type of farm built underground as well as a large-scale but flat (or single-story) farm. A greenhouse utilizing solar light only, however, cannot be a tall multistory structure, so it would be difficult to call it a vertical farm even if it were large in scale.

Interestingly, large windowless poultry houses for the mass production of eggs or chickens with or without a raised floor, which have been commercialized for nearly a half century, are seldom referred to as vertical farms.

In most PFALs, the cultivation beds are placed horizontally on each tier of the cultivation rack with the vertical distance between the tiers ranging from 0.5 to 1.5 m. In a limited number of PFALs, however, the cultivation beds are arranged vertically or inclined, hung or stood upright. The word "vertical" in reference to vertical cultivation beds is, of course, unrelated to the word "vertical" in vertical farm.

2.2.2 The term “plant factory” and its classification

2.2.2.1 *The term “plant factory”*

The term “plant factory” was probably used in 1974 for the first time in a technical committee report on the concept and design of a plant factory published by the Japan Electronics and Information Technology Industries Association (JEITIA, 1974; Takakura, 2020). The committee proposed a design concept of a plant factory with respect to the following: (1) the automatic transportation of plants from the seeding area to the shipping area, (2) automation for labor saving, (3) environmental control for the enhancement of growth and labor saving, (4) efficient utilization of light, electric/fuel energy, and land, and (5) an overall structural design encompassing logistics and sales. In 1976, the technical committee published its final report in which it presented a basic plant factory design 40 m wide, 40 m long, and 10 m high for growing leafy vegetables, fruit vegetables, and other crops under solar light (JEITIA, 1976).

The term “plant factory” was popularized, to some extent, by a paperback book by M. Takatsuji entitled *Plant factory—to new home gardening from cultivation without soil* (Takatsuji, 1979). The author used the term plant factory to mean a facility enabling scheduled and stable production of high-quality plants with the use of artificial and/or natural (or solar) light. Since then, the term plant factory gradually came into use as a general term.

2.2.2.2 *PFAL and PFSL (plant factory with solar light)*

From 2010 to 2014, Japan’s Ministry of Agriculture, Forestry, and Fisheries provided subsidies for research, training, and business concerning plant factories. The term “plant factory with solar light (PFSL)” was coined by the Ministry to mean a Dutch-style large-scale greenhouse with environmental control and automated handling units. According to this definition, a PFSL with or without supplemental lighting was considered to be one type of Dutch-style greenhouse. Since then, both the terms PFAL and PFSL have been used in Japan and, to some extent, in China, Taiwan, and Korea. In these countries, the term plant factory includes both PFSLs and PFALs. This is why the term PFAL has been increasingly used since 2010 to avoid the confusion between PFALs and PFSLs (Fig. 2.3).

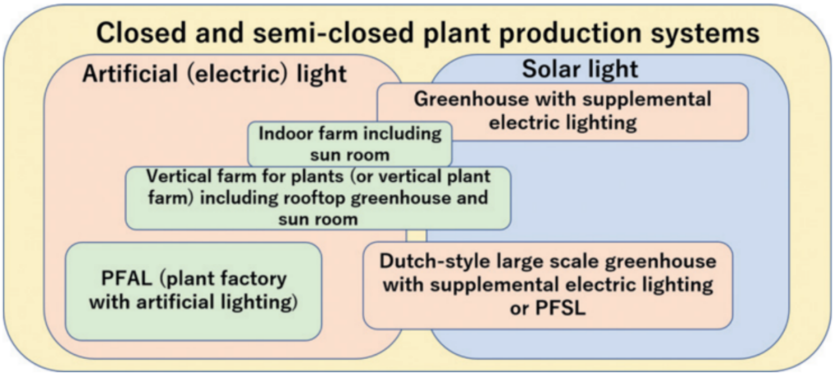

FIGURE 2.3 Diagram showing the differences in light sources of various closed and semiclosed plant production systems.

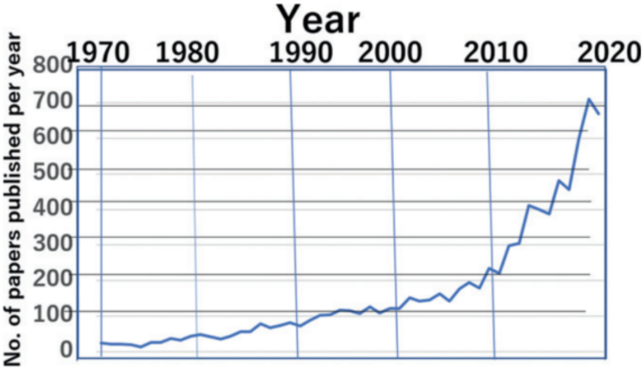

FIGURE 2.4 Yearly trend in No. of papers on plant factory published in journals during 1970–2019 (Total: 8894). https://app.dimensions.ai/discover/publication?search_mode=content&search_text=plant%20factory&search_type=kws&search_field=text_search&order=date. *By courtesy of E. Hayashi and N. Hiramatsu.*

On the other hand, from around 2015, PFAL R&D and business have been more popular than their PFSL counterparts in Japan. Therefore, as of 2020, the term plant factory more often only refers to a PFAL.

Fig. 2.4 shows a yearly trend of the number of research papers with the title of plant factory/plant factories or PFAL/PFALs (excluding the terms vertical farm/vertical farms and vertical farming) published during 1970–2019. The number in 2020 was sevenfold the number in 2000 and threefold the number in 2010.

2.2.3 Definition of the cultivation room in the PFAL

The PFAL is a special type of plant factory that exclusively uses artificial light to produce any kind of plants such as leaf, fruit, head, and root vegetables and herbs without the use of pesticides and herbicides. A PFAL generally consists of a cultivation room, dressing room, air shower room, precooling room, and shipping room (Kozai et al., 2020). This section discusses the cultivation room only.

Produce from a PFAL can be served fresh in salads without the need to wash with tap water before cooking or eating. Requirements and recommendations of the cultivation room of the PFAL described below apply to requirements and recommendations described in Chapters 12 and 13.

2.2.3.1 Requirements of the cultivation room

2.2.3.1.1 Design factors

(1) All walls and roofs are optically opaque (no solar light is transmitted to the cultivation room).

(2) The cultivation room is almost (but not completely) airtight under normal operation conditions (the number of air exchanges of the cultivation room is around 0.02 h^{-1}).

(3) Ventilation fans are installed for use in emergencies such as extremely high CO_2 concentration, high gas concentrations of volatile organic compounds, fire, etc.

(4) Walls and floors are thermally well insulated to minimize heat energy exchange between the interior and exterior of the cultivation room and to prevent water condensation on the internal surfaces of walls and floors (the heat transmission coefficient of the walls/floor is 0.1–0.5 W m^{-2} $°C^{-1}$. The value should be lower in hot and cold regions).

(5) Almost all water vapor transpired from plants is condensed and collected at cooling panels of air conditioners for cooling, and the condensed water is returned to the nutrient solution tank for recycling. Around two-thirds of the lamps are always turned on to ensure that some air conditioners are always turned on for cooling to remove the heat energy generated by the lamps even on cold nights (See Fig. 4.5 in Chapter 4 and Section 8.5 in Chapter 8).

(6) Hydroponic cultivation systems including NFT (nutrient film technique), DFT (deep flow technique), aeroponic, and drip irrigation systems are used.

2.2.3.1.2 Management factors

(1) All personnel entering the cultivation room through the air shower room must change into sanitized clothing and put on a sanitized mask, cap, shoes, and gloves.

(2) No pesticides and herbicides are used.

(3) Only inorganic fertilizer is supplied to the cultivation beds of hydroponic cultivation systems. If organic fertilizer is used, it is first decomposed into inorganic fertilizer using microorganisms before being supplied to cultivation beds.

(4) If the nutrient solution is circulated for recycling, it is first sterilized using filters, UV radiation and/or ozone gas, and/or is filtered through fine substrate layer with special types of microorganisms.

(5) Each of the following environmental factors is maintained independently at time-dependent setpoints: (1) room air temperature, (2) photoperiod, (3) CO_2 concentration in the cultivation room, and (4) electric conductivity and nutrient solution pH.

(6) Sanitary conditions are inspected daily and are maintained.

(7) Measures are taken to prevent the growth and spread of algae in the substrate, nutrient solution, and other wet places in the cultivation room.

2.2.3.2 Recommendations for the cultivation room

(1) Room air pressure is kept slightly higher (5–10 Pa) than the atmospheric air pressure outside to prevent dust and insects from entering the cultivation room.

(2) Each of the following environmental factors is maintained independently at time-dependent setpoints: (1) vapor pressure deficit or relative humidity of the room air, (2) spectral photon flux density distribution (SPFDD) just above the canopy surface, (3) PPFD just above the canopy surface, and (4) air current speed above the canopy surface. The spatial distribution of each environmental factor is relatively uniform in the plant canopy.

(3) On the other hands, the SPFDD and PPFD are affected by the density, height, structure, and optical properties of the plant canopy even when photosynthetic photon flux and its spectral photon flux distribution of light emitted from the lamps remain unchanged, due to changes in the spectral reflection and absorption of light by leaves over time. The air current speed over the plant canopy is also affected by the density, height, and structure of the plant canopy.

FIGURE 2.5 A PFAL with red LEDs built in 1998 at Iwata, Shizuoka Prefecture, Japan, for commercial production of leafy vegetables. *Courtesy of Hisakazu Uchiyama.*

(4) Electricity generated by natural energy such as solar energy is partially or exclusively used for operation of the PFAL.
(5) Seeding, transporting, harvesting, packing, shipping, and washing are partly or mostly automated or robotized.

Some of the requirements and recommendations described above can be realized only at a relatively large-scale PFAL (Fig. 2.5).

2.2.4 Commercialization of PFALs in Japan

PFALs using high-pressure sodium lamps were first commercialized in the early 1980s for the production of leaf lettuce plants. In 1998, a PFAL with red LEDs and 10 tiers was built for commercial production of leafy vegetables (Fig. 4.4; Watanabe, 2011). In 2000, two PFALs with fluorescent (FL) lamps each were built near Tokyo for commercial production of leafy vegetables, one with 7 tiers (Fig. 4.5) and the other with 10 tiers. In 2003, a closed transplant production system with 4 tiers and FL lamps was commercialized (Fig. 2.6; Kozai et al., 2004).

Most PFALs built in and after 2015 use white LEDs (broad band LED with blue, green, and red light). As of 2020, over 200 PFALs are in operation commercially, and around 10 PFALs with white LEDs are producing 2000−5000 kg of leafy vegetables daily. Research on PFALs conducted during 1960−2010 by Takakura and his group members is summarized in Takakura (2019) (Fig. 2.7).

FIGURE 2.6 A PFAL with fluorescent lamps built in 2000 at Kashiwa, Chiba Prefecture, for commercial production of leafy vegetables. *Courtesy of Wataru Shirao.*

FIGURE 2.7 Closed transplant production system with fluorescent lamps commercialized in 2003. *Partially adopted from Kozai, T., Chun, C., Ohyama, K., 2004. Closed systems with lamps for commercial production of transplants using minimal resources. Acta Hortic. 630, 239–252.*

2.2.5 The words "factory," "artificial," and "natural"

This section describes the author's understanding, which is neither scientific nor technical, of the words "factory," "artificial," and "natural" in relation to PFALs.

2.2.5.1 *The word "factory"*

"Factory" means a building or a group of buildings where goods are manufactured or assembled chiefly by machine (the Oxford Dictionary of English). In Japan and some other countries, elderly people tend to have a negative image of factories, which they may associate with chimneys spewing clouds of smoke and discharging environmental pollutants, monotonous jobs, and drab uniforms, etc., which were actual phenomena that characterized many factories until the 1980s.

On the other hand, since around 2000, many young people have a positive image of factories manufacturing goods such as food and confectionery products, computer software, electric appliances, motorcars, soft drinks, and alcoholic beverages. They may associate factories with a clean and comfortable working environment, safe and light work, skilled workers, diversified small quantity production and advanced technology, etc. Accordingly, the term "plant factory" has recently become increasingly accepted in a positive light in Japan and possibly many other countries. The majority of young people tend to like both factory-manufactured products and hand-made or natural products.

2.2.5.2 *The word "artificial"*

According to the Oxford Dictionary of English, "artificial" means "made or produced by human beings rather than occurring naturally, especially as a copy of something natural." Some people dislike the word artificial when used in association with plants and foods, probably because they think that plants should be grown or produced under solar light or natural (outdoor) conditions. They tend to prefer the term "electric light" to the term "artificial light." On the other hand, many people accept the word artificial when used in association with nonfood words such as artificial satellite, artificial intelligence, and artificial teeth.

2.2.5.3 *The word "natural"*

According to the Oxford Dictionary of English, "natural" means "existing in or derived from nature, not made or caused by humankind." "Nature" refers to phenomena of the physical world collectively including plants, animals, landscape, and other features and products of the earth as opposed to human-made phenomena or human operations. In this context, electric light is considered to be artificial light even when the electricity is generated by natural energy such as wind power, solar energy, hydraulic power, geothermal energy, or biomass. People who have a positive image of "nature" tend to forget that "volcanic eruption," "earthquake," "tsunami," "hurricane/typhoon," etc., are natural phenomena.

2.2.5.4 *4 images of the words "factory," "artificial," and "natural"*

Persons who have a positive image of factories and do not have any negative impressions of the word artificial will probably tend to use the term "plant factory," while persons who have a positive image of the word farm and do not have any negative impressions of the words nature or tall building will probably tend to use the term "vertical farm." On the other hand, some elderly people may remind an America classic book "*Grapes of Wrath*" *by* John Steinbeck, which evokes the struggles of migrant farmworkers under harsh weather.

People's impressions of words such as factory, artificial, and natural largely depend on their cultural background as well as their own personal background, religion, personality, philosophy, and other factors, so it is difficult to define terms that will be acceptable to all people. On the other hand, since these terms are now used frequently in scientific papers and books, they need to be clearly defined in a scientific context.

2.2.6 Toward sustainable plant production systems

2.2.6.1 *Sustainability*

Any plant production system to be developed in the coming years needs to be sustainable. Sustainability refers to the ability for such a system to coexist ecologically, environmentally, economically, and socially under specific resource constraints within the surrounding human society and ecosystems for many decades or centuries (Wikipedia, https://en.wikipedia.org. 2020/10/17).

Sustainable development is defined as development that "meets the needs of the present without compromising the ability of future generations to meet their own needs" (United Nations, General Assembly, 1987). However, this concept might appear to be paradoxical since development is considered to be inherently unsustainable. In this context, overcoming the paradox of developing sustainable PFALs and/or sustainable vertical farms will be a major challenge.

2.2.6.2 *Changing the existing PFALs to be more sustainable*

No technology is perfect, and almost all technologies have strengths and weaknesses. Despite some people's negative image of factories, we can continue to use the term plant factory while making efforts to improve the image of existing types of factories by improving their design, management, and use to be more sustainable so that people working in factories and people living nearby feel more comfortable.

There are so many factories in various industries with so many people working inside throughout the world. Simply changing the word factory to a word that has a nicer ring to it will not improve the factory itself. Likewise, if people have a negative image of farms, we should make efforts to improve the image of existing farms by changing them to be more sustainable.

When the term "closed plant/transplant production system" was first used in 2000 (Kozai et al., 2000, 2004), many people thought that the term "closed" was inappropriate because the word had a negative connotation, which was true at that time. Recently, however, people have come to view this term more positively. Likewise, people's impressions of PFALs can also improve if they are proven to be sustainable plant production systems.

The same applies to light sources. If it is shown that artificial light generated by natural energy and stored in batteries for future use is more ecologically and economically sustainable for year-round stable production of quality plants than uncontrollable, inconsistent natural (or solar) light, people's impression of artificial light will change. Such a change will depend on resource productivity (= yield divided by resource input) and monetary productivity (= (unit economic value x yield) divided by (unit cost of resources x resource consumption)) for particular plant species, the purpose of production, and the availability of resources (See, Chapters 12 and 13).

2.2.7 Conclusion

Vertical farms including PFALs can be useful in our society only when they contribute to achieving a sustainable production system of food, feed, and other biological products, reducing CO_2 emissions and waste such as plant residue and urban waste, and helping cities to become ecosystems rather than parasites (Despommier, 2010).

Among its functions, the PFAL will play an important role as a system for absorbing CO_2 from the air through photosynthesis, producing clean water vapor through stomata of leaves, and converting light energy, water, and inorganic fertilizer to carbohydrates and other essential nutrition elements. These photoautotrophic functions of plants will become more and more important in the development of sustainable cities with various types of vertical farms in the coming decades. Establishing clear definitions of the terms frequently used in the field of vertical farming is essential to promote research, development, and widespread practice of vertical farms.

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CHAPTER

3

Role and characteristics of PFALs

Toyoki Kozai
Japan Plant Factory Association, Kashiwa, Chiba, Japan

3.1 Introduction

The primary purposes of this chapter are to clarify the role of PFALs in agriculture and our society in the forthcoming decades, and to compare the environmental characteristics of conventional (or existing) PFALs with those of ideal PFALs. The industry of PFAL with use of LEDs has a history of only 20 years or so, compared with the greenhouse industry's history of around one century and open-field modern agriculture of a few centuries. Thus, most aspects of PFAL research, technology, and business are still immature and at the initial stages of development.

On the other hand, advances in recent technologies such as artificial intelligence (AI), the Internet of Things (IoT), virtual reality (VR), augmented reality (AR), camera-image processing, fifth generation communication network (5G), and LEDs have been remarkable. These advanced technologies are efficiently incorporated into PFALs only when they are designed and managed with the appropriate concept and methodology in line with the fundamental and essential environmental characteristics of PFALs that have an appropriate vision, mission, values, and goals. In fact, there have been many efforts to introduce these advanced technologies into PFALs, although there seem to be only a few successful cases as of 2020. After the spread of Covid-19, the technologies described above have been introduced to unmanned or automated stores and restaurants. Similar technologies can be introduced to develop user-friendly PFALs.

In this chapter, the following PFALs topics are discussed: (1) Vision and mission, (2) Types of plants and products suited for production in PFALs, (3) Essential features of PFALs and reasons behind high resource use efficiency (RUE), (4) Characteristics of conventional PFALs, (5) Characteristics of an ideal PFAL, and (6) Important research and development topics not fully discussed in this book. This chapter discusses issues related to the cultivation room only and does not include issues on other PFAL areas such as the changing room, shipping room, bathroom, and office.

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3.2 Vision, mission, values, and goals of PFALs (Kozai, 2019: Kozai et al., 2020a,b)

It is essential to have a clear vision, mission, values, and goals when addressing global and local issues in areas such as food, resources, the environment, and quality of life before designing a PFAL (Fig. 3.1). Achieving the vision, mission, values, and goals also requires decisions on strategies, tactics, and approaches needed in management and operation. This book discusses possible problems and the potential of PFALs based on the vision, mission, values, and goals described below.

3.2.1 Vision: to construct and manage a sustainable production system to produce value-added functional plants

A PFAL needs to be ecologically, environmentally, sociologically, and economically sustainable and beneficial to the local, regional, national, or global society at a time when urban populations are growing and consumer demand for safer, healthier, and more affordable functional foods is increasing on the one hand, and the agricultural population, water supply for irrigation, agricultural land area, and other resources such as ores containing phosphate and potassium for fertilizer are diminishing on the other hand.

A PFAL must be a CO_2 absorbing/fixing plant production system that maximizes CO_2 assimilation by photosynthetic plants and is designed for sustainable production of functional plants including vegetables, herbs/medicinal plants, ornamental plants, and transplants, excluding staple food plants primarily consumed for their calories or energy, such as wheat, maize, and rice, although transplants of these staple crops can be produced in a PFAL. The staple crops include wheat (*Triticum aestivum*), maize (*Zea mays*), and rice (*Oryza*

FIGURE 3.1 PFAL pyramid consisting of the vision, mission, strategy, tactics, and management/operation.

sativa), root and tuber crops such as cassava (*Manihot esculenta*) and potato (*Solanum tuberosum*), legumes such as soybean (*Glycine max*), and fruit crops such as banana (*Musa* spp.).

3.2.2 Mission: to maximize the yields and quality of produce in a resilient way and in a pleasant working environment, with minimum resource consumption and waste generation

Quality criteria for produce include safety, composition, and concentration of functional and nutritional components, taste, color, texture, appearance, shelf life, uniformity, and hardness/softness. Resources consumed during plant production include working hours, electricity for lighting and air conditioning, water for irrigation and cleaning/washing, fertilizer, land area, seeds, CO_2 for plant photosynthesis, and other consumables such as substrate and packaging. Waste generated includes plant residue, wastewater containing fertilizer, waste heat energy generated by lamps, used plastic materials, and other consumables and contaminants, which may cause negative impacts on the environment outside PFALs. Contaminants contained in produce include small dead insects, dust, and other small foreign substances.

3.2.3 Values: the basic theory and methodology of PFAL design and management are applicable and adaptable, with minimum modification, to any type of PFAL in any society, location, and climate

A PFAL is just one component of a local ecosystem in a region and is integrated with other biological and energy conversion systems to improve local environmental, social, and economic sustainability. The basic theory and methodology of PFAL design and management must be universal and applicable in a simple way to any type of PFAL, regardless of physical scale and application, with minimum modification of design and management.

3.2.4 Goals: to contribute to achieving the 17 Sustainable Development Goals and 169 targets by 2030 (Seth et al., 2019)

Countries are expected to achieve the Sustainable Development Goals (SDGs) by 2030 (refer to Chapter 4). After 2030, new targets for sustainability, social welfare, and ethical production will be set. Global Action Programs such as education for sustainable development, and environmental, social, and corporate governance criteria are also moving in the same direction.

In view of the SDGs and emerging technologies that will come to the forefront in the period from 2025 to 2030 (Fig.3.2) (Kozai, 2019a; Kozai et al., 2019b, 2020a), the design of any PFAL should envision an ideal or ultimate PFAL based on a new vision, concept, methodology, and technologies that reflect future SDGs and technologies.

FIGURE 3.2 Roadmap for sustainable PFALs achieving the SDGs and beyond.

3.3 Subgoals of PFALs associated with the SDGs

The adoption of methods and systems suggested in the following subgoals helps PFALs achieve the SDGs.

3.3.1 An energy- and material-autonomous PFAL

It is possible to construct an energy- and material-autonomous PFAL by adopting a combination of the following methods and systems: (a) an efficient lighting system in a PFAL for converting electric energy to light energy (or photosynthetic photons), (b) an efficient photosynthetic conversion system (carbohydrate synthesis and accumulation in plants from CO_2, H_2O, and fertilizer under light) at any plant growth stage, (c) an efficient aerial and rootzone environmental control system, (d) efficient secondary metabolite production and morphogenesis in plants, (e) selection and introduction of cultivars suitable for PFALs, (f) an efficient hydroponic plant cultivation system, (g) integration of various biological and energy/material conversion systems such as aquaculture, mushroom cultivation, fermentation and air-conditioning systems, (h) use of renewable energy such as solar, biomass, wind, hydraulic, and thermal for generating electricity required for lighting, aerial and rootzone environmental control, and the operation of machines, and (i) reducing, reusing, and recycling of waste such as plant residue and wastewater.

3.3.2 Food chain system

The aim is to develop a food chain system for PFALs with minimum resource consumption and loss of produce (Fig. 3.3). Resource consumption and loss of produce (mostly plant residue) during plant production can be reduced significantly through optimal production scheduling and management, aerial and rootzone environmental control, and selection of cultivars.

After shipment from a PFAL, produce is transported to destinations such as local grocery stores, restaurants, convenience stores, schools, community centers, and homes by

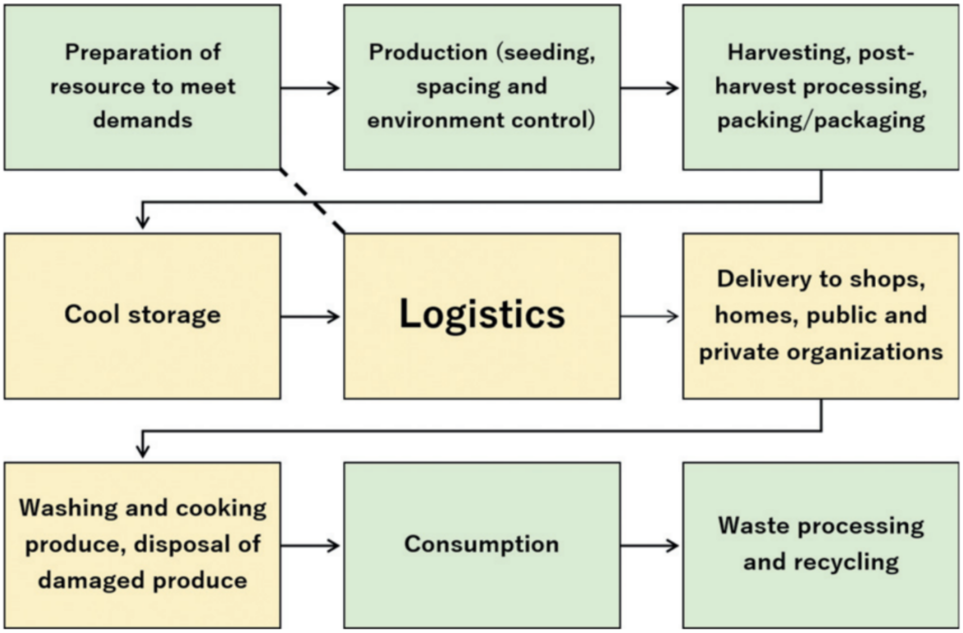

FIGURE 3.3 Resource consumption stemming from cool storage, shipping, transportation, and loss of produce due to damage in a food system chain can be reduced through local production for local consumption of pesticide-free, clean produce with a long shelf life.

minimizing food loss, food quality impairment, food mileage, and time and cost for delivery. A PFAL for local production for local consumption can significantly reduce resource consumption and food loss during transportation.

3.3.3 Conversion of resources into produce and waste

The goal in PFAL design and operation is to maximize production of produce of the highest quality with the minimum use of resources and minimum generation of waste. Fig. 3.4 shows the process of converting resources into produce and waste during the plant production process in a cultivation room.

3.3.4 Multipurpose PFALs

Multipurpose mini- or micro-PFALs can be developed for a wide range of purposes including education, training, self-learning, indoor gardening, small group entertainment, and hobbies (Takagaki, 2020). The software and hardware for mini- or micro-PFALs are the same as for large-scale, commercial PFALs. Users can easily grasp the principle of photosynthesis, the circulation of water and carbon, fertilizer (nitrogen, phosphate, potassium, etc.), plant growth, energy and mass balance, and environmental control. Any actual PFAL can be connected to a virtual PFAL or a PFAL simulator, just like a user-friendly computer game, flight simulator, or car simulator (Kozai, 2018a).

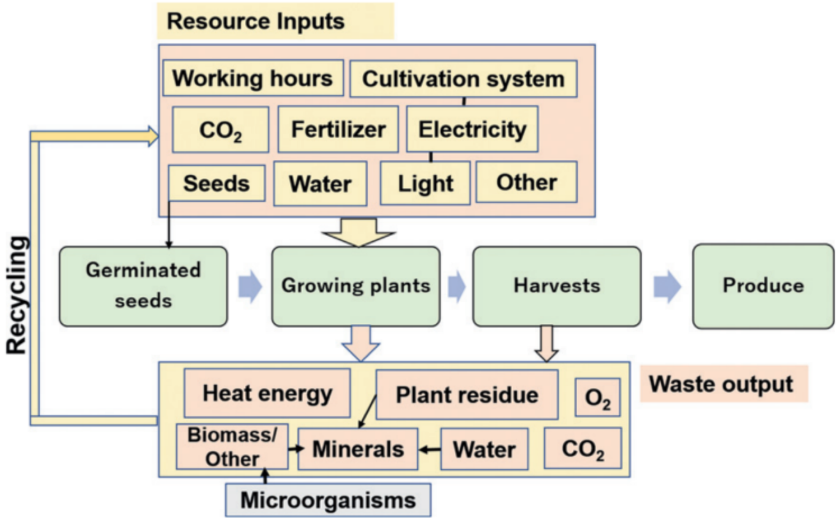

FIGURE 3.4 Conversion of resources into produce and waste during the production process in a cultivation room.

3.3.5 Human resource development

Creating human resource development programs for PFAL designers, engineers, managers, and diverse end users is vital for achieving the SDGs (see Chapter 4 for details). There is a need for software programs that allow users to enjoy learning the principles and concepts of environmental effects on plant growth, efficient energy conversion processes, and the circulation of water, CO_2, and nutrient elements such as nitrogen, phosphate, and potassium in a plant ecosystem, while they grow plants and manage the production process for food and other purposes while considering the resource and monetary productivity (Chapters 12 and 13).

3.3.6 Pleasant work environment

The aim is to create a comfortable, safe, constructive, and inclusive work environment for everyone including the elderly and persons with disabilities, regardless of gender, religion, age, nationality, or personality, to create a friendly and enjoyable community.

3.3.7 Implementation of advanced technologies and models

Advanced technologies and models must be introduced into well-designed PFALs. Advanced technologies include AI, VR, AR, 5G (wireless technology for digital mobile networks), IoT, phenotyping (plant trait measurement), and open databases via the Internet for the development of flexible, user-friendly, sustainable PFALs. Robot and OMICS (genomics, metabolomics, proteomics transcriptomics, etc.) technologies can also be introduced to large-scale PFALs.

Models include mechanistic, multivariate statistic, behavior (or surrogate), and AI models (Kozai, 2018a). Using such technologies, evolutional PFALs can be realized with high resource and monetary productivity (refer to Chapters 12 and 13 for details) and high scalability, traceability, and adaptability.

3.4 Types of plants and products suited for production in PFALs

Functional plants produced in PFALs can be used for various purposes. Table 3.1 shows potential and actual uses of plants produced in PFALs. Only leafy fresh vegetables and various kinds of transplants are currently commercialized widely.

Types of plants shown in Table 3.1 are called functional plants in this book, and exclude staple crops such as maize, wheat, rice, and potatoes. Compared with staple crops, functional plants generally require lower photosynthetic photon flux density (PPFD of 100–200 μmol m^{-2} s^{-1}), shorter cultivation periods (a few weeks to a few months) or year-round cultivation, and higher spatial and/or aerial planting density. Besides, monetary value

TABLE 3.1 Main uses of functional plants produced in PFALs. Only leafy vegetables and various types of transplants are currently commercialized widely.

No.	Category	Uses
1	Functional foods	Fresh leafy, fruit, root, and bulbous vegetables
		Processed leafy, fruit, root, and bulbous vegetables
		Dried and freeze dried leafy, fruit, root, and bulbous crops
		Edible flowers and accompaniments/trimmings
		Edible seaweeds (Nori, genus *Porphyra*), spirulina, euglena, and other edible aquatic plants
2	Drink and food additives	Medicinal/herbal components, juices, sweeteners, flavorings, seasonings, and natural coloring pigments
3	Medicine and healthcare goods	Supplements, cosmetics, perfume, aroma, and specialty oils
		Chinese medicine, alternative medicine, and pharmaceuticals including *Cannabis sativa* L. for medical, recreational, and industrial uses
		Potassium (K^{+}) poor or rich lettuce, Fe^{++} (iron) rich spinach, polyphenol and antioxidant rich vegetables, algae, euglena, spirulina, waxy barley, etc.
4	Disease, virus, and insect-free transplants	Seedlings, micropropagated and grafted transplants, rooted or unrooted cuttings, propagules (stolons, microtubers, minitubers, bulblets), lawn/turf seedling mats, bedding plants, moss, etc.
5	Ornamentals, fruits, and others	Miniature or dwarf ornamentals and fruits, plants for interior decoration, bouquets, pot plants, cut flowers, etc.
6	Functional staple crops	Staple crops containing special functional components showing medicinal and/or health care effects

(economic value per kg of produce) of functional plants is 10—100 times higher than staple crops (Kozai et al., 2020a). PFALs are particularly suitable for growing relatively short plants (30—50 cm in height) with relatively upright leaves, which grow fast under relatively low PPFD and high CO_2 concentration (1000 ppm or higher).

3.5 Land area required for producing fresh vegetables

China ranked the highest in annual vegetable consumption per capita with 328 kg in 2013. Average world annual vegetable consumption per capita was around 135 kg in 2017 according to the Food and Agriculture Organization of the United Nations. Assuming that 5% of 135 kg (0.05×135) or 6.75 kg/person of fresh vegetables are supplied annually by PFALs with 10 tiers in an urban area with a population of 10 million, 67,500,000 kg (6.75×10^7) or 67,500 metric tons of vegetables can be produced annually in PFALs with a total floor area of around 270 ha (67,500 tons ÷ 250 tons/ha).

On the other hand, around 27,000 ha of open fields or around 2700 ha of greenhouses located in a temperate region is necessary to produce the equal amount of 67,500 tons of vegetables annually. As of 2017, there are 47 cities in the whole world with a population of over 10 million, of which three have over 30 million residents, namely Tokyo, Jakarta, and Shanghai.

Martellozzo et al. (2014) wrote that urban agriculture (UA) would require roughly one-third of the total global urban area to meet global vegetable consumption of urban dwellers; the area ratio is higher where urban population density is higher. This estimate does not consider how much urban area may actually be suitable and available for UA. This study suggests that we need to produce a substantial percentage of vegetables in PFALs and greenhouses instead of open fields.

3.6 Essential features of PFALs and reasons behind high resource use efficiency

3.6.1 Resource and waste elements

Types of resource elements supplied to a PFAL and waste elements emitted from the PFALs are shown in Fig.3.5 and 3.6, respectively. In a PFAL, the supply rate (amount supplied per unit time) of each resource element can be accurately measured. Besides, rates of net photosynthesis and water uptake by plants in a cultivation room can be relatively accurately estimated based on CO_2 and water balance equations (Kozai, 2013), because the cultivation room of a PFAL is almost airtight and thermally well insulated.

Similarly, uptake rates of nutrient elements such as N, P, K, Mg (magnesium), and Ca (calcium) by plants from a nutrient solution in a cultivation bed can be estimated based on nutrient ion balance equations, although this type of automatic controller is not available commercially as of 2020 (Kozai et al., 2018a). Furthermore, the emission rate of each waste element can be measured relatively accurately. Moreover, data on production rates of plants, marketable parts of plants, their unit price for sale, and unit cost of each supply element are easily collected daily.

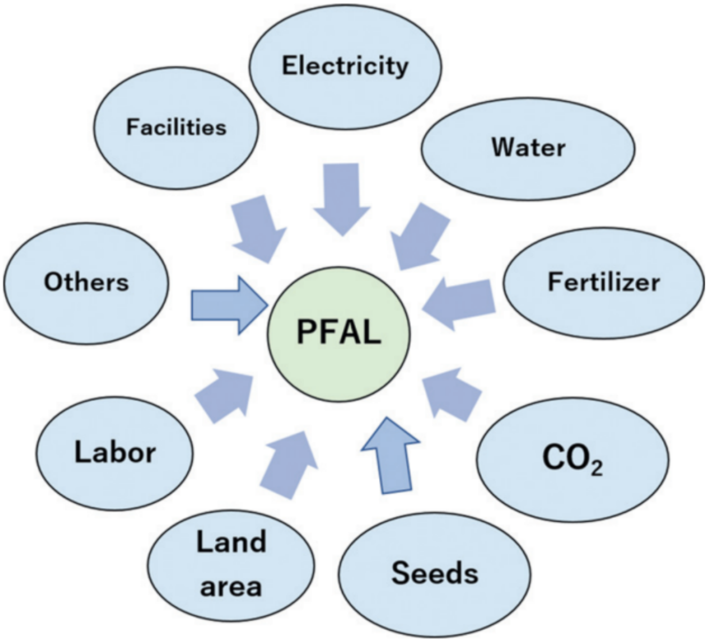

FIGURE 3.5 Resource elements supplied to a PFAL.

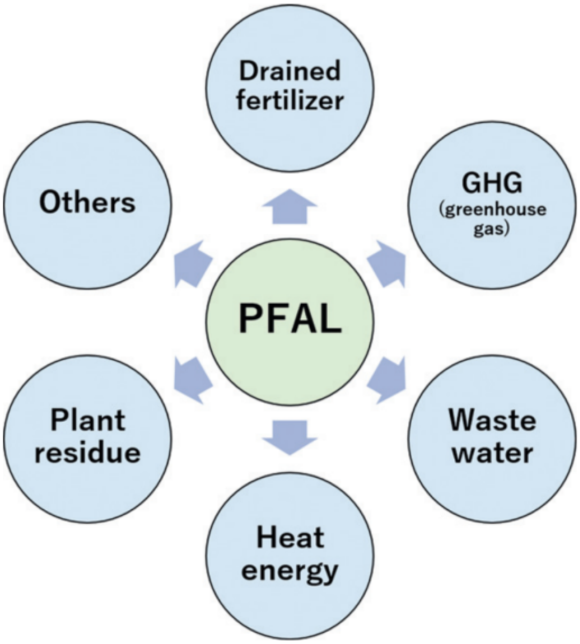

FIGURE 3.6 Waste elements emitted from a PFAL.

3.6.2 Basic characteristics of PFALs

3.6.2.1 *Airtightness*

A highly airtight and thermally insulated cultivation room guarantees (1) no invasion of viruses, microorganisms, insects, small animals, dust, or the like through air gaps between the interior and exterior of the cultivation room; (2) minimum exchanges of CO_2 and water vapor through air gaps between the interior and exterior of the cultivation room; (3) no influence of weather on the environment inside the cultivation room; and (4) the recycling of CO_2 and water in the cultivation room.

CO_2 respired by plants that accumulates in a cultivation room is reused (assimilated) through plant photosynthesis during a period of light exposure. This improves CO_2 use efficiency to nearly 100% in an airtight cultivation room. CO_2 respired by humans in a cultivation room is also absorbed by plants under light. Nearly 95% of water vapor transpired by plants is condensed and collected by air conditioners during cooling and is recycled as irrigation water. High airtightness means the number of air exchanges in a cultivation room is lower than 0.02 h^{-1} or so.

On the other hand, forced ventilation through a gas filter is required when the following abnormalities are found: (1) Unfavorable gases, such as volatile organic compounds (VOCs) produced by plants and/or structural elements and odors emitted by humans, accumulate in a cultivation room; (2) CO_2 concentration reaches a level higher than around 1500 $\mu mol\ mol^{-1}$ (or ppm) in the presence of workers in a cultivation room; (3) Pathogenic microorganisms and/or viruses are detected in room air; and (4) An extreme environment such as a high air temperature (e.g., 40 °C) is recorded due to a fire and/or malfunction of air conditioners and/or a lighting system. The upper limit of CO_2 concentration in a room varies between 1000 ppm and 5000 ppm, depending on countries, types of building, exposure time, etc.

3.6.2.2 *Thermal insulation*

High thermal insulation of the cultivation room is required to (1) minimize the impact of fluctuations of the outside air temperature, wind speed/direction, atmospheric pressure, and vapor pressure deficit (VPD) on inside air temperature, CO_2 concentration, and VPD and air movement in a PFAL; (2) reduce or inhibit condensation of water vapor on inside walls, floors, etc., by keeping their surface temperatures higher than the dew point temperature of room air; and (3) minimize heat energy exchange through walls and the floor between the interior and exterior of a cultivation room. Desirable heat transmission coefficients of walls/floors are around 0.1–0.2 $W\ m^{-2}\ °C^{-1}$.

3.6.2.3 *Highly hygienic and safe work environment*

Clean (or hygienic), semihygienic, and contaminated areas in a PFAL are physically separated from each other. Special caution is required to prevent the invasion, growth, and propagation of (1) bacterial pathogens such as *Escherichia coli* O157: H7 or *Bacillus dysentericus* which cause diseases in humans (hemorrhagic diarrhea), (2) plant pathogens such as *Pythium aphanidermatum which* causes roots to rot; (3) pest and unpleasant insects such as mites (Arachnida) and lake flies (Chironomidae); and (4) small animals such as mice. In conformity to ISO22000, the Japan Plant Factory Industries Association released the following guidelines for the safety of produce: (1) CFU (colony forming units) should be lower than 1000 per g (fresh weight), (2) no use of pesticides during cultivation, (3) *E. coli* negative, and (4) no foreign matter present (JPFIA, 2020).

Once biological contaminants mentioned above are spread in a cultivation room, all the plants inside need to be taken out to the outside for disposal by burning, and the empty cultivation room is disinfected often by a fumigant (smoking). Then, it takes more than 1 month to harvest new produce after disinfection. In this sense, biological contamination poses the highest risk/damage to a PFAL.

3.6.3 Observability, controllability, traceability, predictability, and reproducibility

To achieve high and stable resource and monetary productivity with minimum resource consumption and waste emission throughout the year, high observability, controllability, traceability, predictability, and reproducibility of a cultivation room are indispensable.

High airtightness and thermal insulation of a cultivation room with reliable sensors are required to keep observability high regardless of the weather outside. High observability of a cultivation room with reliable actuators is required to keep controllability high. High degrees of observability and controllability lead to a high degree of traceability of resource consumption, waste emission, plant production rates, the room environment, equipment operation, etc (Fig. 3. 7). High reproducibility and predictability can be achieved by using various types of plant growth and production management models including AI models and of IoT sensors.

High degrees of observability, controllability, traceability, predictability, and reproducibility are special features of a next-generation PFAL that ensures continuous reductions in production cost and waste emission, high RUE, and daily estimation of resource and monetary productivity (Chapters 12 and 13). These measured and estimated variables can be visualized together with other related data on a computer display in its cultivation room and operation room and can be used for further analysis and prediction of production processes.

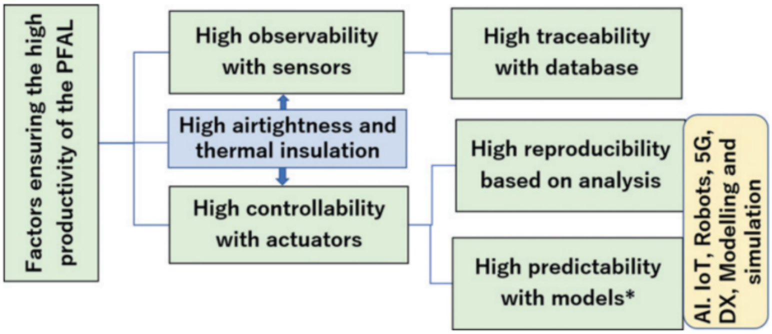

FIGURE 3.7 Models: Mechanistic, multivariate statistical, behavioral (or surrogate), and artificial intelligence (AI) models. IoT stands for Internet of Things. 5G: the fifth generation technology standard for broadband cellular networks. *DX*, digital transformation.

3.6.4 Measurement and estimation (see Chapter 8 for details)

3.6.4.1 Environmental factors

Main environmental factors to be controlled in a PFAL include air temperature, CO_2 concentration, temperature, total ion concentration or electric conductivity, and pH of nutrient solution. Other environmental factors to be controlled or frequently monitored include VPD, air current speed, lighting cycle or photoperiod, PPFD, dissolved oxygen concentration, and flow rates of nutrient solution. Spectral photon flux of lamps and spatial PPFD distribution in cultivation space need to be checked every half year or so.

3.6.4.2 Resource supply and production rates

All resource supply rates can be measured relatively easily, both continuously and online (in real time), for their control and analysis. Time courses of the operating status of all major equipment can also be recorded for analysis. Resources include working hours, electricity for lighting and air conditioning, water for irrigation and cleaning floors and cultivation panels, CO_2 for promoting plant photosynthesis, fertilizer (nutrient solution), seeds, substrates, seed trays, and disinfectants. Daily production rates of produce, wastewater, and waste (plant residue, etc.) can also be measured.

3.6.4.3 Rate variables and RUE estimation

Rates of net photosynthesis, dark respiration, and water uptake or transpiration can be estimated online based on the CO_2 and water balance of a cultivation room. Sensible and latent heat generation and conversion in a cultivation room can be separately estimated based on the heat and water balance equations. The energy conversion process from electrical to chemical energy (carbohydrates in plants) can also be estimated.

The variables measured or estimated above can be used to calculate use efficiencies of electricity (electric energy), light energy (photosynthetic photons), water, CO_2, fertilizer, seeds, and substrates. The coefficient of performance (COP) of air conditioners can be estimated as a function of air temperature difference between the interior and exterior of a cultivation room and the ratio of a cooling load to cooling capacity.

3.6.4.4 High RUEs almost realized

(1) Water and CO_2 use efficiencies are nearly 100% due to their recycled use.
(2) Seed and transplant use efficiencies are nearly 100% (all seeds and transplants are grown to marketable plants).

3.6.4.5 RUEs to be improved

(1) Nutrient elements use efficiencies of conventional PFALs that adopt a nutrient solution recycling system are 0.7–0.8, which need to be improved to nearly 100% hopefully with the use of a one-way (noncirculating) nutrient solution supply system (refer to Section 10).
(2) Substrates (plant-supporting material) and other consumables need to be used at minimum levels or recycled to minimize waste emission.
(3) Cultivation beds need to be always occupied with high-quality plants, and all produce is marketable to achieve a cultivation bed use efficiency of 100%. Spatial density of plants (no. of plants m^{-3} or m^{-2}) in a cultivation room is high at any plant growth stage.

(4) All parts of all plants need to be used, marketed, and/or sold, resulting in no plant residue including physically or physiologically damaged parts of plants.

(5) If only leafy or aerial parts are useable or marketable, the dry weight percentage of roots needs to be minimal as long as the roots do not restrict the growth of aerial parts. The percentage of root weight of whole leafy vegetable plants is often 10%–15% in conventional PFALs.

3.6.4.6 Resource and monetary productivity

Resource and monetary productivity can be estimated and visualized using data on resource supply rates, production rates, resource use efficiencies and unit costs for each resource and waste element, and unit sales prices of produce (refer to Chapters 12 and 13 for details).

Reasons behind potentially high RUEs and resource/monetary productivity are described above (Sections 6.3 and 6.4). These reasons and benefits of PFALs are all related to fundamental characteristics of PFALs described in this chapter. Those benefits are particularly useful to contribute to solving issues concerning food, the environment, resources, and quality of life discussed in Chapter 1.

3.7 Aerial environmental characteristics of conventional PFALs to be improved

Spatial distributions of these environmental factors inside a plant canopy are generally interrelated with each other. These distributions are also interrelated with the architecture (leaf area index, leaf angle, size, shape, etc.) of a plant canopy and physiological status (stomatal conductance, chlorophyll concentration and fluorescence, water potential, etc.) of plants and their changes with time. Accordingly, rates of net photosynthesis, transpiration, and thus growth of plants are interrelated with the environment, canopy architecture, and physiological status.

3.7.1 Light

Under downward lighting conditions, the leaves at the uppermost level of a plant canopy receive more light energy than those at lower levels, particularly in a densely populated plant canopy (e.g., Oikawa, 1977). Then, the PPFD decreases exponentially as the depth increases from the top to the bottom of a plant canopy (Fig. 3.8). Then, the net photosynthetic rate of

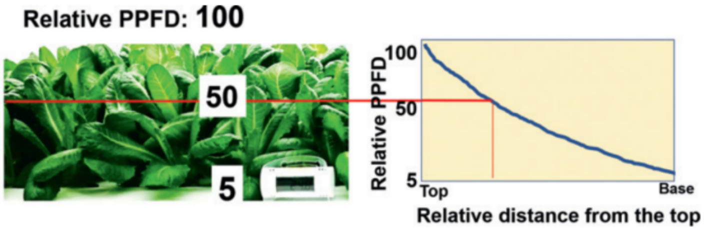

FIGURE 3.8 Scheme showing exponential decrease of PPFD within a densely populated plant canopy. Air current speed shows a similar decrease within the densely populated plant canopy.

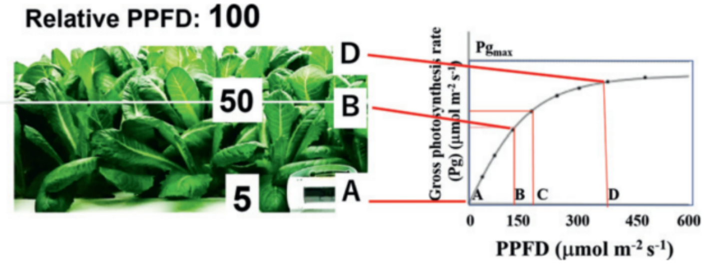

FIGURE 3.9 The exponential decrease of PPFD suppresses the canopy photosynthesis and thus growth. A similar decrease of air current speed within the densely populated plant canopy.

leaves decreases with the increase in the depth of a plant canopy (Fig. 3.9). A similar decrease of air current speed is observed within a densely populated plant canopy (The PPFD in the plant canopy fluctuates if the leaves are fluttered by air currents).

3.7.2 Aerial environmental characteristics and plant response

In a conventional PFAL with downward lighting, the aerial environment inside a plant canopy is significantly different from that just above the plant canopy. Moreover, spatial uneven distributions of environmental factors within a plant canopy are often observed especially when the plant canopy is densely populated. These spatial uneven distributions of environmental factors generally suppress the growth rate of a plant and spatial uniformity of plant growth and chemical components. The environmental factors include PPFD, spectral photon flux density distribution, air temperature, CO_2 concentration, air current speed, and VPD.

If the PPFD is spatially uniform at an appropriate level in a plant canopy regardless of the canopy's depth, the net photosynthetic rate of the whole plant canopy should increase significantly, and the decrease in net photosynthetic capacity of lower leaves due to their senescence may be prevented (Zhang et al., 2015; Joshi et al., 2017). Three-dimensional computer simulation work on the light environment in a plant canopy may be useful to evaluate and optimize a lighting system of PFALs (Saito et al., 2020).

3.7.3 Vertical uneven distribution of spectral photon flux density in a plant canopy

A vertical uneven distribution of spectral photon flux density (SPFD) also exists within a plant canopy in downward lighting conditions using white LEDs emitting blue, green, red, and far-red light. This is because the transmittance of a horizontal single green leaf is around 5% for blue (400−499 nm) and red (600−699 nm) photons, about 20% for green (500−600 nm) photons, and around 40% for far-red (700−800 nm) photons (Taiz and Zeiger, 2006). Thus, percentages of green and far-red photons increase among photons with a wavelength of 400−800 nm with increases in the depth of a plant canopy and the depth of each leaf (Terashima and Saeki, 1985; Sun et al., 1998; Nishio, 2000).

This vertical profile of SPFD inside a plant canopy affects photosynthesis and morphogenesis, and thus the growth and development of a plant canopy (Folta, 2019). In fact, green and far-red photons contribute significantly to plant productivity and RUE, especially in plant production under white LEDs containing a significant percentage of green photons (Smith et al., 2017). It should be noted that percentages of green and far-red photons emitted from white LEDs vary 15%–40% and 0%–5%, respectively, depending on the type and quantity of phosphors covering LED tips (Kozai et al., 2016). Also, as of 2020, most PFALs for commercial production use white LEDs due to their high cost performance (i.e., high performance and low cost).

3.7.4 Profiles of air temperature, CO_2 concentration, and water vapor pressure (Kitaya et al., 1998, 2004; Kitaya, 2016)

In conventional PFALs, horizontal air current speeds and thus gas diffusion coefficients in a plant canopy are significantly higher above and around upper leaves than around lower leaves, which affect the vertical distribution (or profile) of air temperature, CO_2 concentration, and VPD inside a plant canopy (Kitaya, 2016).

Fig. 3.10 shows that the air temperature around leaves during a photoperiod is about 2 °C higher than the air temperature above and in the lower part of an eggplant seedling canopy. The leaf temperature is also 1–2 °C higher than the air temperature. CO_2 concentration is at its lowest at the uppermost part of a plant canopy where the net photosynthetic rate is highest. The VPD is at its highest at the wet substrate surface due to evaporation and at its second highest around leaves due to transpiration.

These profiles are considerably affected by the PPFD, air current speed, and plant canopy architecture. In a tomato seedling canopy, as schematically shown in Fig. 3.11, only hypocotyls (or stems) with two small cotyledons exist in the lower part of the canopy (lower than 30 mm), so that air moves horizontally relatively freely in this space (0–30 mm above the substrate surface).

On the other hand, there is no such empty space in a leaf lettuce canopy shown in Fig. 3.9. Thus, the vertical profile can be more clearly observed in the plant canopy shown in Fig. 3.9 than those of a seedling canopy shown in Fig. 3.10.

Similar uneven spatial distributions of flow speeds, dissolved O_2 concentrations, nutrient element concentrations, and nutrient solutions pH are observed in a hydroponic cultivation bed.

3.7.5 Vapor pressure deficit (VPD)

The VPD in a cultivation room full of plants reaches nearly 0 kPa (relative humidity or RH is 100%) within 10–20 min after all the lamps are turned off at the same time (dark period). This is because air conditioners stop due to a very low cooling load (no heat energy generation from LEDs).

Alternately turning on and off lamps avoids this very low VPD and keeps the VPD and room air temperature at set levels. Air conditioners remove not only sensible heat to lower room air temperatures but also latent heat (water vapor) and dehumidify room air. In this way, the VPD is kept at preferable levels (around 0.3 kPa or relative humidity [RH] of around 80%) all day (Kozai et al., 2019a; Kozai, 2018b).

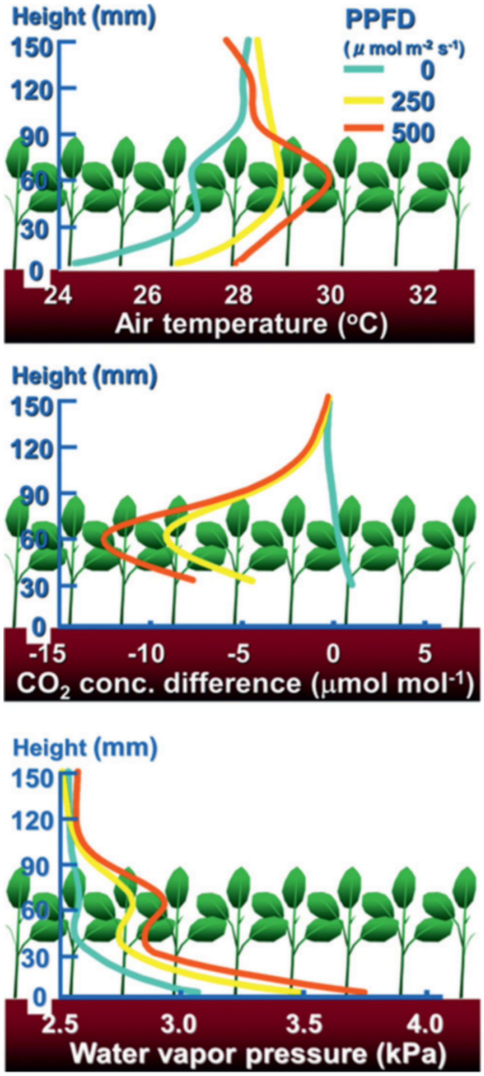

FIGURE 3.10 Vertical distributions of air temperatures, CO_2 concentrations, and water vapor pressure above and within an eggplant (*Solanum melongena* L.) seedling canopy (90 mm high and leaf area index of 6) at PPFD of 0, 250, and 500 mmol/m^{-1}/s, and horizontal air current speed of 0.1 m/s. CO_2 concentration, air temperature, and water vapor pressure were 380 ppm, 28°C, and 2.4 kPa (RH: 65%), respectively, at a height of 150 mm from the substrate surface. *Reproduced from Kitaya, Y., Shibuya, T., Kozai, T. and Kubota, C., 1998. Effects of light intensity and air velocity on air temperature, water vapor pressure, and CO2 concentration inside a plant canopy under artificial lighting conditions. Life Supp. Bios. Sci. 5, 199–203 with permission.*

It should be noted that the VPD decreases (RH increases) with an increase in the total leaf area in a cultivation room, because leaves are a supply source of water vapor to room air. On the other hand, at around 24 °C, the VPD reaches around 1.5 kPa (RH at 50%) or greater when no plants are growing in a cultivation room.

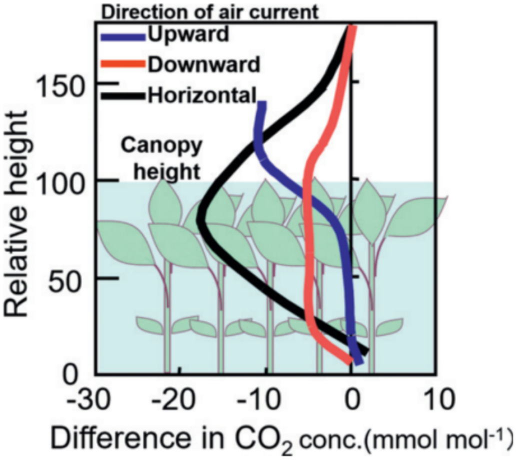

FIGURE 3.11 Vertical distribution of CO_2 concentrations during photoperiod above and within tomato (*Lycopersicon esculentum* Mill.) seedling canopy as affected by air current direction. The reference CO_2 concentration was taken at the air inlet of the system. *Reconstructed from Shibuya T., Tsuruyama J., Kitaya Y., Kiyota M., Enhancement of photosynthesis and growth of tomato seedlings by forced ventilation within the canopy Sci. Hortic. 2006, 218–222 with permission.*

3.7.6 Improving the aerial environment in a plant canopy

3.7.6.1 *Vertical distributions of CO_2 concentrations*

Fig. 3.11 shows the vertical distribution of CO_2 concentration during a photoperiod above and inside the tomato seedling canopy, due to the effects of forced air currents in an upward, downward, or horizontal direction. The figure shows that downward and upward air currents provide relatively uniform vertical CO_2 concentrations in the plant canopy, and that CO_2 diffusion into the stomata of leaves is more pronounced than with horizontal air flows (Shibuya et al., 2006). The CO_2 concentration around the uppermost leaves is about 15 μmol mol^{-1} higher in upward and downward air currents than in horizontal air current. Similar effects of nutrient solution flows in water and nutrient element uptake need to be examined to determine an ideal hydroponic cultivation system.

3.7.6.2 *Promoting net photosynthesis by increasing CO_2 concentration and air current speed*

CO_2 is assimilated (photosynthesized) by leaves mostly through stomata on the abaxial side of leaves only under light, while CO_2 is continuously emitted mostly through stomata under both light and dark (dark respiration) conditions. A very small amount of CO_2 moves through the epidermis of leaves. Dark respiration (or CO_2 emission) increases with an increase in leaf temperature and dry mass of leaves. The net CO_2 exchange rate at leaves or a canopy under light is referred to as the net photosynthetic rate.

Fig. 3.12 shows that the net photosynthetic rate of a tomato seedling canopy increases with an increase in CO_2 concentration and horizontal air current speed over the plant canopy (Kitaya et al., 2004). The net photosynthetic rate generally increases with an increase in CO_2 concentration in a range of 0–1000 μmol $μmol^{-1}$ and air current speed in a range of 0.1–1.0 m s^{-1} at PPFD of around 250 μmol m^{-2} s^{-1}. The optimal air current speed depends on the VPD, LAI, average leaf angle, and PPFD.

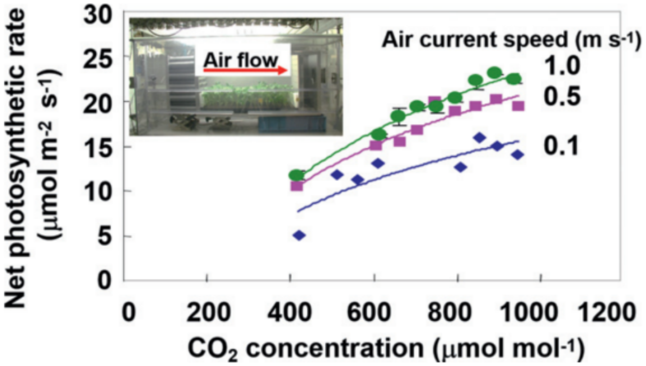

FIGURE 3.12 Net photosynthetic rate of a tomato (*Lycopersicon esculentum* Mill.) seedling canopy as affected by CO_2 concentration and horizontal air current speed at PPFD of 250 mmol/m^{-1}/s and air temperature of 28°C. *Reconstructed from Kitaya, Y., Shibuya, T., Yoshida, M., Kiyota, M., 2004. Effects of air velocity on photosynthesis of plant canopies under elevated CO2 levels in a plant culture system. Adv. Space Res. 34, 1466–1469 with permission.*

3.8 Improving subsystems of a cultivation room

3.8.1 Increasing electric energy use efficiency

In a PFAL, 30%–40% of electric energy is converted to light (or photosynthetic radiation) energy by lamps, 60%–90% of the light energy emitted by lamps is received by leaves, and a portion (around 10% at most) of light energy absorbed by pigments such as chlorophylls in leaves is converted to chemical energy as carbohydrates through photosynthetic activity. As a result, between 1.8% (100 × 0.3 × 0.6 × 0.1%) and 3.6% (100 × 0.4 × 0.9 × 0.1%) of electric energy consumed by lamps is converted to chemical energy as carbohydrates in plants. A portion of carbohydrates is converted to proteins, lipids, and various secondary metabolites. Thus, the percent conversion from electric to chemical energy or electric energy use efficiency is an important parameter to be improved.

3.8.2 Reducing electricity consumption per kg of produce

One of the weaknesses of conventional PFALs with LEDs is that they require 7–9 kWh of electricity, as of 2018, for lighting, air conditioning, etc., to produce 1 kg of fresh leafy vegetables such as leaf lettuce (refer to Chapter 12). This electricity cost accounts for about 20% of total production costs of PFALs in Japan. The following improvements are expected to reduce this electricity consumption per kg of produce to 5–7 kWh:

(1) Increase photosynthetic photon efficacy of LED luminaires by 10% (from 2.5–3.0 μmol J^{-1} in 2020 to 2.8–3.3 μmol J^{-1}). (The term "efficiency" is used when the unit of nominator and denominator is the same, otherwise the term "efficacy" is used). In theory, the maximum efficacy is 3.34 μmol J^{-1} at 400 nm (wavelength), 3.80 μμmol J^{-1} at 455 nm (blue), 4.63 μmol J^{-1}J at 555 nm (green), 5.52 μmol J^{-1} at 660 nm (red), and 5.85 μmol J^{-1} at 700 nm. Thus, the efficacies can be further improved in the near future. See Chapters 5–7 and Chapters 16–19 for further details on efficient use of LEDs.

(2) Increase the ratio of light energy received by the leaves of a plant canopy to light energy emitted from lamps by improving the lighting system and plant canopy architecture.

(3) Optimize SPFD and their spatial and temporal distributions in a plant canopy to achieve higher resource and monetary productivity for various kinds of plants.
(4) Optimize the hydroponic cultivation system and the composition, strength, and supply rate of nutrient solution.
(4) Breed or select cultivars with better phenotypes or plant traits.
(5) Ensure a dynamic environmental control to meet production objectives.

Fortunately, costs have been decreasing year after year for power generation by renewable energy, battery storage, and smart grids.

3.8.3 Increasing harvest index

Electric energy use efficiency can also be improved by increasing the harvest index (HI), which is defined as the weight ratio of marketable part of plants to the whole plants. Production of leafy vegetables and transplants using PFALs is commercialized widely because the HI of leaf vegetables ranges between 0.8 and 0.9 and the HI of transplants is nearly 1.0. However, the HI of fruit vegetables is generally around 0.5. If aerial (or leafy) parts of dwarf root vegetables such as carrots, turnips, and radish are edible, the HI of root crops would improve to nearly 1.0.

The quality and quantity of produce demanded by crop producers, buyers, and/or consumers vary according to the purpose of sale, purchase, or use, but higher quality and lower costs are always required. Such requirements are partially satisfied when all parts (leaves, petioles stems, roots, and flowers/flower buds if any) of the plant can be used, marketed, and/or sold, with virtually no plant residue or loss of plants (i.e., HI = 1.0). The economic or social value per kg of produce is maximized when the quality of all parts of all plants is equally highest. This ideal goal needs to be kept in mind when designing and managing actual PFALs toward next-generation PFALs.

3.8.4 Developing various models for plant production process management

Modeling and simulation work required for PFAL design and management include the following: (1) energy and material balance and energy/material conversion processes using mechanistic models; (2) spatial distributions of environmental factors (PPFD, UV (ultraviolet) and far-red flux density, air current speed, CO_2 concentration, and VPD) above and within a plant canopy and spatial distributions of plant traits (e.g., concentrations of chemical components) within a plant canopy; (3) P = f (G, E, M) model (See Section 3.11.2), or photosynthetic growth, development, and morphogenesis of plants, and secondary metabolite production models; (4) production scheduling, production process control, and financial management; (5) management of risks such as outbreaks of diseases/pest insects/pathogens, sanitation breaches, power outages, machine malfunctions, natural disasters, economic disturbances, and/or changes in consumer preferences; and (6) integration of all the above models into one PFAL management model.

When conducting simulations of points 3, 4, and 5 mentioned above, behavioral (or surrogate) and AI models such as machine learning including deep learning models can be efficiently used in addition to mechanistic and multivariate statistic models. It should be

FIGURE 3.13 Left: The area ratio of total cultivation rack to floor area is about 0.5, and the area ratio of total cultivation bed area to floor area of cultivation room is about 5, in a typical conventional PFAL with 10 tiers for commercial production. Right: The area ratio of total cultivation rack to floor area of cultivation room is about 0.8, and the area ratio of total cultivation bed area to the floor area is nearly 10 $(= 0.8 \times 4 \times 3 = 0.96)$ in a three-stacked cultivation system modules (CSMs) each with 4 tiers with total of 12 $(=3 \times 4)$ tiers for commercial production (to be built in 2022). The area for automatic push-in/pull-out of cultivation panels is located at right side of each CSM. The plants are harvested after transported to a separate space. *Photo: by courtesy of PlantX Corp.*

noted that, in modeling, the relationships among variables in those models are often nonlinear and time dependent and show hysteresis effects in some cases.

3.8.5 Improving rack and cultivation bed area ratios in conventional PFALs

In most PFALs, nearly half of the floor area of a cultivation room is occupied by multi-tiered cultivation racks, and the other half is used for plant management and transportation of plants and supplies as well as maintenance of cultivation systems (Fig. 3.13). For example, in a PFAL with 10 tiers and a rack area ratio (ratio of rack area to floor area) of 0.5, the cultivation bed area ratio (ratio of total cultivation bed area to floor area) is equivalent to 5.0 (0.5×10). Thus, in this cultivation room, the ceiling height and distance between tiers and the rack area ratio, which is 1.0 at the maximum (i.e., no walkway on the floor), are the keys to improving production capacity per floor area. This figure can be doubled with the use of Cultivation System Modules (CSMs, see Section 3.11.12) shown in Fig. 3. 13, Right.

3.9 Environmental characteristics of ideal PFALs

3.9.1 Environmental uniformity of ideal PFALs

This section describes the environmental characteristics of ideal PFALs for maximizing resource productivity, that is, having the highest yield and quality with minimum resource inputs and emissions of environmental pollutants (revised from Kozai, 2019a). At a glance, the ideas for maximizing resource productivity presented below may seem unrealistic and impractical. However, it is important to understand the characteristics of ideal PFALs before settling for less due to difficulties at present.

3.9.1.1 Strategy for optimal environmental control

During the vegetative growth stage of plants, aerial and rootzone environmental factors other than photosynthetic photons need to be controlled primarily so that photosynthetic photons are converted to chemical energy of carbohydrates in leaves and translocated to

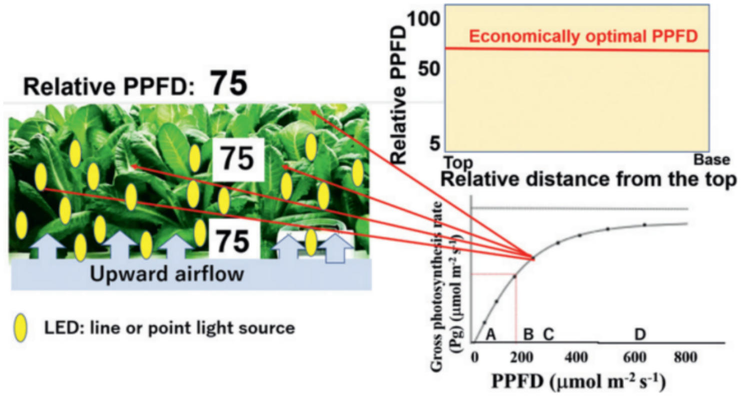

FIGURE 3.14 Omni-directional lighting and enhanced air movement within a densely populated plant canopy will promote the photosynthesis, growth, and their spatial uniformities. Even distributions of photosynthetic photons and air currents to all parts of all leaves maximize photosynthesis and thus plant growth.

appropriate parts of plants at the highest efficiency and lowest costs as intended by PFAL managers. This is because electricity cost for photosynthetic lighting is the highest of all environmental control costs.

3.9.1.2 *Hypothetical idea of a lighting system*

A hypothetical idea of an ideal lighting system is that all photosynthetic photons (or light energy) emitted by lamps are distributed and/or received equally by all parts of all leaves in a canopy (Fig. 3.14) although a small fraction of the photons are unavoidably absorbed by petioles, stems, etc., of plants. Air currents are also distributed uniformly to all parts of all leaves in a canopy.

This hypothetical idea is based on the PPFD−Pg (gross photosynthetic rate) curve shown in the lower right of Fig. 3.14. The physiological efficiency of Pg over PPFD is highest at PPFD near zero, but the absolute value of Pg is too low; the economic efficiency is highest and absolute value of Pg is appropriate between points B and C; and lowest at point D or greater in Fig. 3.14.

Under ideal LED lighting conditions, photosynthetic photons emitted by LEDs, P_{flux}, are distributed equally to all parts of all leaves with total leaf area of A_{leaf}. The photosynthetic photons received by a unit leaf area are expressed as r_p*(P_{flux}/A_{leaf}) μmol m^{-2} s^{-1} where r_p is a ratio of photosynthetic photons received by leaves to that emitted by the LEDs. By increasing the r_p value and minimizing the spatial variation of (P_{flux}/A_{leaf}), the canopy photosynthesis is maximized.

Zhang et al. (2015) and Joshi et al. (2017) indicated that upward supplemental lighting from below the canopy delayed senescence of the outer leaves and increased the fresh weight of marketable leaf lettuce plants by around 20%. This upward lighting system could be further improved in the near future.

As a general rule, the ideal lighting conditions described above can be realized by arranging a number of small light sources such as LEDs around and inside the plant canopy to provide light from above, below, the sides, and inside the canopy and/or by applying projection mapping technology to use laser lighting.

With the use of the lighting system shown in Fig. 3.14, the plants' morphology and metabolism change considerably, and this positively or negatively affects the economic value of the produce. A uniform light environment in a plant canopy has the following effects: (1) Geometrical relationships between the source (photosynthesizing parts) and sink (accumulating parts of translocated carbohydrates) of plants are changed; (2) All leaves of a plant canopy relatively equally act as producers of carbohydrates; (3) Senescence of lower leaves due to low PPFD is suppressed; and (4) Phytohormone balances in individual plants are changed.

Little is known how plants respond to this spatially uniform light environment in a plant canopy, and this research area is a big challenge. Besides, an optimal lighting system depends on plant canopy architecture (e.g., leafy vegetables, head vegetables, fruit vegetables, etc.) and the purpose of production (served fresh in its original shape, supplied fresh but shredded, supplied as processed produce, etc.).

3.9.1.3 *Lighting for head vegetables (see also Chapter 23)*

In the case of head vegetables such as cabbage, Chinese cabbage, and head lettuce plants, lighting with green LEDs or white LEDs emitting a considerable percentage (e.g., 40%) of green photons over photosynthetic photons may be beneficial because green photons penetrate inside their heads (Fig. 3.15). Green photons inside the heads enhance the biosynthesis of chlorophyll and other secondary metabolites (Saengtharatip et al., 2020). Green LEDs can be inserted into the base of head vegetables 1−3 days before or after harvest for greening the inside of the head (Fig. 3.15. Lower right). This type of lighting technology can be applied when the greening and subsequent changes in chemical components inside heads are beneficial to improve the value of head vegetables.

3.9.1.4 *Spatial uniformity of environmental factors other than photosynthetic photons*

Uniform and/or maximum plant growth can be expected by achieving spatial uniformity of all aerial and rootzone environmental factors including spectral distribution of light, air current speed, CO_2 concentration, VPD, and nutrient solution flow speed in the root zone.

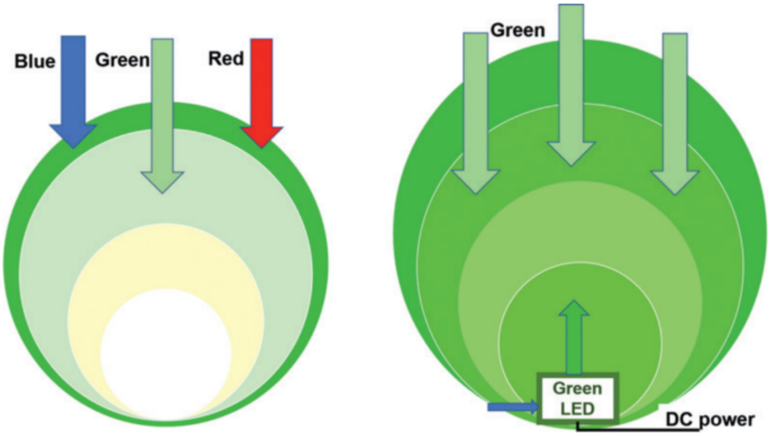

FIGURE 3.15 Scheme demonstrating that green light penetrates more deeply than blue and red light into the core of head vegetables such as lettuce, cabbage, and Chinese cabbage.

Spatially uniform CO_2 concentration and VPD can be realized by enhancing the air movement in a plant canopy at a speed of around 0.5 m s^{-1} Spatially uniform rootzone environmental factors are more difficult to achieve than aerial ones but can be realized by enhancing the movement of nutrient solution at a speed of around 0.1 m s^{-1}. Namely, spatial uniformity of environmental factors is always associated with the movement of air and nutrient solution.

Spatially uniform environmental factors in a plant canopy are expected to enhance spatial uniformness of growth, development, and secondary metabolite production in a plant canopy and plant growth. However, little is known on how plants respond to these spatially uniform environment factors in a plant canopy.

3.10 Ideal hydroponic cultivation systems for PFALs

3.10.1 Conventional and ideal hydroponic cultivation systems

Type 1 in Fig. 3.16 shows a scheme of a typical hydroponic cultivation system, which is often referred to as an NFT (nutrient film technique) or DFT (deep flow technique) system (Lu and Shimamura, 2016). In Type 1, the nutrient solution stored in a nutrient solution tank is pumped up and supplied from one end of the cultivation bed and then flows down slowly to the opposite side of the cultivation bed. The nutrient solution drained from the other end of the cultivation bed flows back in a longitudinal direction to the nutrient solution tank through a slightly inclined pipe or a gutter outside the cultivation bed. A sterilization device with a filtering unit is installed in the middle of a return pipe in most cases.

Clean water mixed with stock solution is added to the nutrient solution tank to replace the nutrient solution absorbed by plants. A portion of the nutrient solution is sometimes drained to the outside when there is an imbalance in ion composition and/or an accumulation of organic acids and/or microorganisms. This type of hydroponic cultivation system is characterized by its recycling use of nutrient solution. Refer to Chapter 9 for realistic and practical hydroponic cultivation systems and to Chapter 10 for aquaponics.

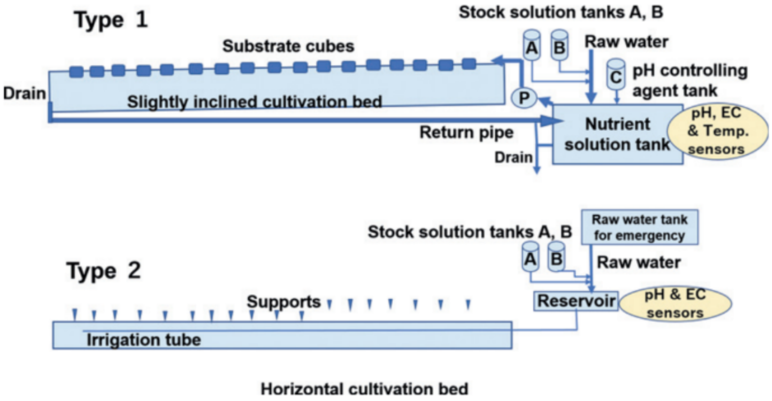

FIGURE 3.16 Hydroponic cultivation systems. Type 1: A conventional system, Type 2: An ideal system.

3.10.2 Design principles of an ideal hydroponic cultivation system

Three important design principles of an ideal hydroponic system are to (1) minimize the overall size, volume, piping/tubing length, and weight of the construction components; (2) minimize the total volume of nutrient solution in a hydroponic system at full production capacity; and (3) supply nutrient solution with optimized composition and strength at an optimum rate (Type 2, Fig. 3.16).

In Type 2, the nutrient solution flows in a one-way (noncirculatory) direction. The cultivation bed is horizontal and without a drain (except for an emergency drainpipe), and the nutrient solution is supplied from small holes along thin irrigation tubes (a few mm in diameter), which is similar to the tubes used in drip irrigation.

This system can significantly reduce the costs of construction components and of a hydroponic cultivation system. The required structural strength of a cultivation rack with multiple cultivation beds containing nutrient solutions can also be reduced considerably.

By installing a highly reliable intelligent controller in Type 2, controllability can be maintained at a high level to optimize the rootzone environment in the cultivation beds. All nutrient element ions are supplied with the water into cultivation beds either intermittently or continuously, and most of nutrient solution ions are absorbed by plants within several hours or so, resulting in nutrient element and water use efficiencies of nearly 100%. Ions that are unnecessary for plants or are minimally absorbed (Cl^-, Na^+, etc.) by plants are not supplied.

To realize a Type 2 hydroponic system, the desirable daily uptake rate of each nutrient element ion by plants must be estimated in advance by using plant growth and environment models. A method to avoid the accumulation of undesirable organic acids emitted by plant roots and sediments of chemical compounds in the cultivation beds needs to be developed.

The ultimate goal of a hydroponic system is to control supply rates, nutrient composition, and nutrient solution strength to meet the exact needs of individual plants based on multiobjective functions of plant cultivation. In this regard, one challenge is to develop such a hydroponic cultivation system with smart software and sensors.

3.10.3 Major characteristics of an ideal hydroponic cultivation system

Major characteristics of an ideal hydroponic cultivation system for PFALs are summarized in Table 3.2.

3.11 Challenges to realize sustainable PFALs

Challenges to realize ecologically, environmentally, economically, and socially sustainable PFALs that are not discussed in this book but would become more and more important as core components in sustainable urban area development include the following:

3.11.1 Breeding of cultivars suited to PFALs

Almost all cultivars (or cultivated varieties) grown in PFALs as of 2021 have been bred for cultivation in open fields or greenhouses. However, the desired genotypes and phenotypes

TABLE 3.2 Major characteristics of an ideal PFAL hydroponic cultivation system.

No.	Factor	Description
1	No circulation of nutrient solution	A return nutrient solution reservoir tank is unnecessary since nutrient solution is delivered via a thin one-way (noncirculating) irrigation tube. Thus, piping to return the drained nutrient solution to its nutrient solution tank is also unnecessary.
2	Recycling of water used in washing or cleaning	Water used for washing/cleaning floors, cultivation panels, etc., and nutrient solution unexpectedly drained from the hydroponic cultivation beds are also recycled after proper filtering and sterilization.
3	Variable nutrient solution supply rates	Nutrients and water are supplied at optimal rates according to the plant species, growth stage, purpose of production, etc., so that no nutrient solution is drained.
4	Variable nutrient solution composition	Nutrient solution composition needs to be adjusted to avoid an imbalance of ions that results in an accumulation of unabsorbed ions in nutrient solution.
5	Zero substrate volume per plant	The use of substrates and time required for handling substrates are none or minimal, which simplifies a cultivation system.
6	Minimum nutrient solution volume per plant	Artificial controllability of nutrient solution is improved, a hydroponic cultivation system is simplified, and initial investment and operating costs are reduced.
7	No propagation and growth of algae and fungi	Propagation and growth of fungi and of unsanitary, unpleasant insects are suppressed due to the absence or low population density of algae in the cultivation room. To maintain such an environment, substrate surfaces, and cultivation beds, floors, and walls must be kept dry.
8	Elimination or control of root Exudates in cultivation beds	Plants exude, from their roots, significant amounts of exudates including allelopathic organic acids such as formic acids, saccharides such as glucose, amino acids such as glycine, and low molecular organics such as citric acid. These exudates often accumulate in cultivation beds and affect plant growth negatively (allelopathy) or positively (feeding beneficial microorganisms around roots) and need to be eliminated or controlled. Root rotting pathogens such as *Pythium* sometimes enter and propagate in the cultivation beds.

(or plant traits) for production in PFALs are different from those for production in open fields and greenhouses. Plant phenotypes suitable for PFALs include the following:

(1) Rapid growth at high CO_2 concentration (1000 μmol mol^{-1} or higher), with low PPFD (100–200 μmol m^{-2} s^{-1}, and in a long photoperiod (20–24 hours a day), without any physiological disorders such as tipburn, intumescence, and necrosis, and producing desired functional chemical components at high concentrations under controlled environments (see Chapter 20 for breeding a new dwarf tomato cultivar for PFAL).

(2) Plant architecture including leaf angle and shape is well adapted to artificial lighting and for easier mechanical or manual harvesting.

(3) Cultivars whose phenotypes such as morphology, color, secondary metabolite production, etc., can be easily manipulated by environmental control, so that multiple products can be derived from one genotype (Folta, 2019).

(4) Cultivars with no resistance to environmental stress and pest insects/viruses because they are grown free from environmental stress and pathogens/pest insects.

(5) Dwarf, compact, and determinate type fruit vegetables such as tomato plants shorter than 0.5 m with short internodes.

(6) Fruiting vegetables with traits of self-pollination or parthenocarpy (fruiting without fertilization of ovules) to avoid the need for artificial pollination by insects, mechanical devices, or humans.

(7) Cultivars suitable for rapid breeding (Watson and Ghosh, 2018).

It should be noted that cultivars with the genetic traits mentioned above can be efficiently bred in PFALs. Furthermore, PFALs can be used as an efficient tool for rapid breeding of indoor, greenhouse, and outdoor plants as well as seed propagation and transplant propagation.

3.11.2 Production of seedlings with uniform phenotype

Production of seedlings with a uniform phenotype is an essential starting point of plant production in a PFAL. Spatial and temporal uniformity of germination time after sowing and unfolding of cotyledonary leaves are the key to uniform seedling production. The seedling or plant phenotype (P) is a function of genotype (G), environment (E), and management (M), or $P = f(G, E, M)$. More specifically, P is a function of seeds' genotype, physiological status of seeds, presowing treatment (priming, coating, etc.) of seeds, chemical, physical, and biological properties of a substrate (or a seed mat), seeds' microenvironment (substrate surface temperature and wetness, contact area of seeds on a substrate, composition and strength of nutrient solution, and SPFD), and human or machine seeding operation (Hayashi et al., 2020). Finding the function $P = f(G, E, M)$ for various types of seeds is a challenge to realize a next-generation PFAL.

3.11.3 Phenotyping

In any commercial PFAL, it is impossible for managers or workers to observe all plants with the naked eye at all times. Plants are elongating their stems, expanding, and moving their leaves even during the dark period. Thus, continuous plant phenotyping is becoming more and more important to determine the optimal environmental factors in a PFAL. Plant phenotypes (or traits) include seed germination (Hayashi et al., 2020), leaf area, leaf angle, number of leaves, plant height, fresh weight, chlorophyll concentration, chlorophyll fluorescence (Moriyuki and Fukuda, 2016), leaf temperature, and chemical composition affecting the quality of produce.

On the other hand, plant phenotypes in a PFAL can be measured relatively easily by using various types of small cameras such as visible, near-infrared, infrared, and/or night-vision cameras with zooming, rotating, mobile, and microscopic functions (Kozai, 2018a). Cost performances of these cameras, related image processing software, and environmental sensors have been improving every year. Time lapse image data on plant phenotypes together with environmental and management data can be used for developing AI and other models.

3.11.4 Power generation using natural energy

Energy autonomy is a key element of sustainable PFALs, because electric energy is indispensable for lighting, air conditioning (mainly cooling), and pumping the nutrient solution. Electricity can be generated using natural energy such as wind power, solar energy, biomass, etc. Besides, the cost performance of batteries for electricity storage has been improving year by year (Uraisami, 2018). Even so, electricity consumption per kg of produce needs to be reduced further.

3.11.5 Life cycle assessment

From the viewpoint of life cycle assessment (LCA), reductions in GHG (greenhouse gas) emission and consumption of N–P–K fertilizer and water per kg of produce are critical to improve the sustainability of PFALs (Kikuchi and Kanematsu, 2019). LCA is a useful tool to quantify environmental impacts and potential impacts based on a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling, and final disposal (Kikuchi and Kanematsu, 2019).

Nicholson et al. (2020) compared economic and environmental performances of supply chains for leaf lettuce produced in open fields, greenhouses, and PFALs. The authors included costs for land area, packaging, and transportation in the calculation of production costs and LCA. CO_2 emission in the supply chains was also considered in the LCA analysis.

This type of LCA research in combination with economic analysis of profitability is becoming more and more important for choosing an optimal combination of plant production system, production planning and management, and location or site to produce a particular crop under given social, economic, and climate conditions. For more information on the profitability of PFALs, refer to Chapters 13 and 14.

3.11.6 Construction and operation of PFALs using renewable materials

For PFAL construction, using reinforced, nonflammable wooden, or plant-derived structural elements, which do not emit VOCs, is preferable to help minimize the use of metals, cement, and fossil fuel–derived plastics, which emit CO_2, during production of structural elements and during construction and maintenance of PFALs.

The sustainability of PFALs can also be improved by (1) using plant-derived consumables for cultivation trays, substrates, packaging, etc.; (2) reducing wasted potassium and phosphate fertilizers to preserve their finite natural resources (rock phosphate and potash ore) (Kikuchi and Kanematsu, 2019); (3) reducing wastewater; (4) using no fossil fuels; and (5) minimizing the traffic or flow lines of workers and produce.

3.11.7 Design, construction, and management of human-centered PFALs

As an antidote to the increasing stress in people's lives today due to urbanization and other factors, the practice of 'nature therapy' has demonstrated that an environment rich in plant life can contribute to the relief of physical and mental anxiety (Miyazaki et al., 2011, Chapter 22). Interaction between humans and plants in urban horticulture even in PFALs is believed to contribute to good health and well-being of people (Lu et al., 2020). Therefore, human-centered PFALs based on nature therapy may become an important objective of PFALs for improving quality of stakeholder's life and quality of produce (Lu et al., 2020).

3.11.8 Circadian rhythm

Circadian rhythms (or biological clocks), as characterized by an endogenous period of nearly 24 h, are ubiquitous in almost all living organisms including plants. Use of this characteristic of plants is expected to improve photosynthesis and growth, and thus PFAL productivity (Dood et al., 2005; Higashi et al., 2015). Or, the DNA related to circadian rhythm can be genetically deactivated to achieve production under a 24-hour photoperiod or for lighting at nighttime or irregular time.

3.11.9 Mycorrhizal/symbiotic fungus and biostimulants

Using fungi, including arbuscular mycorrhizae for symbiosis, in a hydroponic cultivation system is a challenge to realize in next-generation PFALs as appropriate use of renewable organic fertilizer is indispensable for sustainable production of plants. Development of a sustainable system to convert organic fertilizer to inorganic fertilizer holds the key as plants basically uptake inorganic mineral ions as nutrient elements (Kozai et al., 2019a). Beneficial fungi can be used to suppress the growth of pathogenic fungi and decompose unfavorable organic matter. Ensuring compatibility of their symbiosis with strict sanitation control is a challenge. See Chapter 9 for a discussion on use of organic fertilizers in hydroponics. Root exudates such as organic acids, polysaccharides, and low molecular substances accumulated in cultivation beds are known to affect plant growth, but little is known about their role in the ecosystem of a cultivation bed.

3.11.10 Seed grain production of staple crops

Interest in production of staple crops in large-scale PFALs has been growing since around 2020 by some large private companies, national institutes, and universities. Foods from staple crops form the basis of a traditional diet containing relatively high percentage starch and some protein, serving as a major source of energy and nutrients. Staple crops include cereal crops such as maize, wheat, rice, and potatoes.

Until recently, commercial production of staple crops in a PFAL did not attract attention except for basic research on space farming (Wheeler et al. (1993); Wheeler (2006)), because (1) produce can often be stored for 1 year or so; (2) physical and physiological damage due to long distance bulk transportation by ship is limited; (3) international trade is common to balance the supply and demand; and (4) economic value per kg of staple foods is much lower compared with that of specialty or functional foods.

However, yields of those crops in open fields have been vulnerable recently to climate change causing droughts, floods, and high/low temperatures as well as a plague of locusts in Africa and Asia. A shortage of water for irrigation, soil deterioration, decreases in arable land area and/or agricultural workers are also serious in some regions. In addition, international trade has been declining in 2020 due to the Covid-19 pandemic and international political and economic frictions. Besides, some oil-producing countries are interested in commercial production of staple crops in PFALs with solar panels for power generation as the next emerging industry. Thus, ensuring staple foods under the above situations is becoming a political and economic issue in regard to food security in many countries.

It might be practical, in the near future, to produce a portion of high quality seed grains of rice, maize and wheat, and microtubers of potatoes for security reasons in PFALs using electricity generated by natural energy.

3.11.11 Laser lamps as a substitute for LEDs

A solid state laser is widely used in such products as laser pointers used for presentations and barcode scanners. Laser is an acronym for "light amplification by stimulated emission of radiation." A laser differs from other light sources in that it emits coherent light, which can (1) be focused to a tight spot (high intensity); (2) the beam remains narrow over great distances (directionality); (3) emit light with a very narrow spectrum (monochromatic); and (4) produce pulses of light with durations as short as a femtosecond (10^{-15} s). Little is known on how plants respond to the light emitted from a laser lamp, although research on plant growth under laser light has been conducted to some extent (Yamazaki et al., 2002; Murase, 2015; Ooi et al., 2016). No commercial PFALs that use laser lamps are present as of 2021. An advantage of lasers over LED lamps is their higher conversion efficiency from electric to light energy (65%–75% at wavelength of 900–999 nm) (Nogawa et al., 2020).

3.11.12 Development of a cultivation system module and its application

The concept, methodology, design principles, and potential application of a CSM are described in Kozai (2018). A CSM becomes smarter by implementing ideas described in this book. However, this scalable and evolutionary CSM with e-learning software for sustainable production of plants is not actualized yet. Developing a standard and/or open-source CSM will accelerate the achievement of the SDGs and the realization of sustainable societies.

3.12 Conclusion

With a history of only about 20 years, the technological and business development of PFALs with LED lamps is still at an early stage. Advanced technologies such as AI and IoT have just been recently introduced to commercial PFALs. As of 2021, no commercial PFALs using 5G, VR, AR, and/or MR (mixed reality) seem to come into being. Such advanced technologies are most efficiently used in well-designed PFAL hardware, software, and firmware units. It is time for all stakeholders to develop sustainable PFALs to contribute to solving issues concerning food, the environment, resources, and quality of life. In this chapter, basic concepts and methodologies were discussed for designing and managing sustainable PFALs for the next generations.

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CHAPTER

4

Contribution of PFALs to the sustainable development goals and beyond

Toyoki Kozai
Japan Plant Factory Association, Kashiwa, Chiba, Japan

4.1 Introduction

In 2015, more than 190 world leaders committed to achieving 17 sustainable development goals (SDGs) with 169 targets by the year 2030 as a universal call to action to end poverty, protect the planet, and ensure that all people can enjoy peace and prosperity (Sharma and Sobti, 2018; Seth and Suazo, 2019). In short, the 17 SDGs are aiming for: (1) No poverty, (2) No hunger, (3) Good health and well-being, (4) Quality education, (5) Gender equality, (6) Clean water and sanitation, (7) Affordable and clean energy, (8) Decent work and economic growth, (9) Industry, innovation, and infrastructure, (10) Reduced inequalities, (11) Sustainable cities and communities, (12) Responsible consumption and production, (13) Climate action, (14) Life below water, (15) Life on land, (16) Peace, justice, and strong institutions, and (17) Partnerships for the goals.

Under SDG 4 (Quality education), the United Nations Educational, Scientific and Cultural Organization (UNESCO) is responsible for improving access to quality education for sustainable development (ESD) at all levels and in all social contexts, to transform society by reorienting education and helping people develop knowledge, skills, values, and behaviors needed for sustainable development.

In the investment industry and business operations, the SDGs are discussed in relation to environmental, social, and corporate governance (ESG) criteria. These criteria are a set of standards in a company's operations that socially conscious investors use to consider potential investments. Environmental criteria consider how a company performs as a steward of nature. Social criteria examine how a company manages relationships with employees, suppliers, customers, and the communities where it operates. Governance deals with a

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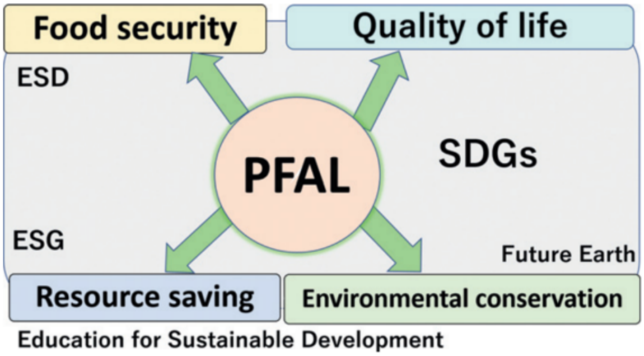

FIGURE 4.1 The PFAL can contribute to achieving the SDGs by solving the four global and local issues in an environment characterized by (1) a declining agricultural population with aging farmers, (2) growing urban populations, (3) increasing demands for higher quality food and lifestyle, and (4) changing global and local climates. ESD and ESG denote, respectively, education for sustainable development, and environment, society, and corporate governance.

company's leadership, executive remuneration, audits, internal controls, and shareholder rights (Chen, 2020). The outbreak of COVID-19, a pandemic which began in early 2020, will continue to affect all aspects of the SDGs, ESD, and ESG, and poses a tremendous challenge for all countries in finding workable solutions (OECD, 2020).

This chapter focuses on how the plant factory with artificial lighting (PFAL) can contribute to achieving the SDGs and related action programs and why the PFAL can be one appropriate and efficient means for achieving the SDGs in today's environment characterized by (1) a declining agricultural population with aging farmers, (2) growing urban populations, (3) increasing demands for higher quality food and lifestyle, and (4) changing global and local climates (Fig. 4.1).

Prior to commencing the discussion of the potential contribution of PFAL to the SDGs, the chapter will present the structure, characteristics, and necessity of the PFAL in Sections 4.2 and 4.3. Therefore, readers already familiar with PFALs can skip these sections. To maintain the independence of this chapter, the description of PFALs in Sections 4.2 and 4.3 partially overlaps with that in Chapters 2 and 8.

4.2 What is a PFAL?

4.2.1 Main components and environmental control factors

A PFAL is a closed plant production system, and its cultivation room consists of a thermally well-insulated, fairly airtight, and optically opaque warehouse-like structure, multitier cultivation units with light emitting diode (LED) lighting and hydroponic cultivation units, air conditioners with circulation fans, a CO_2 supply unit, a nutrient solution supply unit, and an environmental control unit (Fig. 4.2; see Chapter 8 for more details).

Environmental control factors include air temperature, photosynthetic photon flux density (PPFD), CO_2 concentration of the room air, pH, and total ion concentration of the nutrient

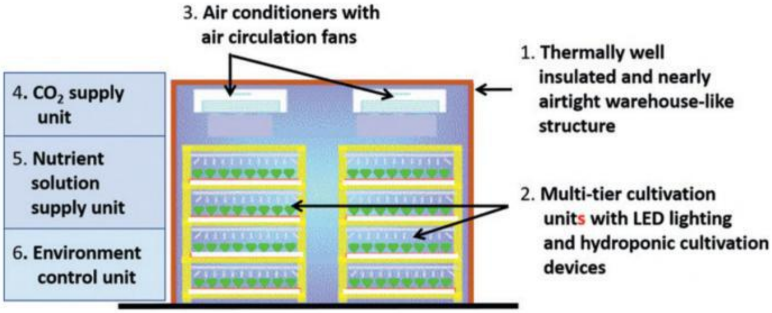

FIGURE 4.2 Six main components of the PFAL cultivation room.

solution. The air current speed, vapor pressure deficit (VPD) or relative humidity (RH) of the room air, and temperature and dissolved O_2 concentration of the nutrient solution as well as the flow speed of the nutrient solution are indirectly controlled within their upper and lower limits.

Since the cultivation room is highly airtight and thermally insulated, all the resource inputs and outputs to and from there can be relatively easily measured and controlled automatically. The resource input and output are not directly influenced by the weather, pest insects, and small animals outside, so the environment in the PFAL can be controlled as desired, and the use efficiency of each resource element can be estimated online based on the measured values of corresponding resource input and output (see Chapter 8 for more details). Thus, the use efficiency of each resource element and the overall resource use efficiency or productivity (or the ratio of yield to cost) can be continuously improved based on the data analyses of the measured inputs and outputs (Kozai et al., 2019a).

4.2.2 Why are airtightness and thermal insulation required?

High airtightness of the cultivation room is required to prevent (1) the invasion of viruses, microorganisms, insects with or without pathogens, small animals, dust, or the like through air gaps, and (2) the loss of CO_2 and water vapor gases through air gaps to the outside. This airtightness also enhances the recycling use of CO_2 and water in the cultivation room, resulting in high CO_2 and water use efficiencies.

Both high airtightness and thermal insulation are required to prevent (1) the impact of weather on the aerial environment of the cultivation room and (2) water condensation on the inner surfaces of walls, roof, and floor (fungi, algae, and some insects propagate and/or grow quickly on wet surfaces), and to ensure that (3) the cooling load for air conditioners or heat pumps is determined only by electricity consumption of lamps, pumps, fans, etc., regardless of weather.

4.2.3 Heating and cooling loads and electricity consumption of equipment

No heating is required even on cold winter nights when more than half of the lamps are turned on, because the heat generated by the lamps is more than adequate for keeping the air temperature of the thermally well-insulated, airtight cultivation room at around 25°C even during outside temperatures as low as −40°C.

On the other hand, the cooling of the cultivation room using air conditioners is required throughout the day, and all year round when most of the lamps are turned on. Electricity consumption for cooling the thermally well-insulated, airtight cultivation room accounts for around 20% of all electricity consumption (lighting, cooling, pumping, etc.) in warmer regions and about 15% in cooler regions (Chapter 8; Kozai, 2013; Kozai et al., 2019a). It is also important to notice that no extra electricity is required to dehumidify the room air or to keep the VPD at around 0.5 kPa or RH of 75% at 25°C if the lamps are turned on. The room air is naturally dehumidified when cooled by air conditioners to keep the room temperature at a set point.

4.2.4 Reduction in maximum electricity consumption by alternating lighting

About 60%–70% of LEDs are alternately turned on all day in the cultivation room in most PFALs. In this case, air conditioners operate all day, even on cold winter nights, to remove heat energy generated by LEDs (Chapter 8). Under such conditions, the electricity consumption for cooling and dehumidification of the room air accounts for 15%–20% of all electricity consumption in the cultivation room, while lighting accounts for 75%–80%, and pumping, air circulation, etc., for about 5% on average annually in regions with a temperate climate.

By alternating the lighting as mentioned above, the electricity consumption for lighting and cooling remains relatively consistent throughout the day. Thus, their maximum values are reduced by about 30% compared to those for all LEDs turned on for 16 h d^{-1} and off for 8 h d^{-1} at the same time, although the total amount of daily electricity consumption for lighting and cooling is the same as those for all LEDs turned on for 16 h d^{-1} and off for 8 h d^{-1} at the same time.

With the same daily cooling load, the daily cost of electricity for cooling is lower at night than in daytime due to higher coefficient of performance (COP) of air conditioners at lower outdoor air temperatures at night. Then, the cooling capacity of air conditioners and the capacity of power supply units can also be reduced by about 30%, resulting in a reduction in the initial cost for air conditioners and power supply units.

Besides, VPD (or RH) is kept relatively constant all day due to continuous lighting of two-thirds of LEDs and continuous cooling as well as dehumidification all day. Under highly airtight, thermally insulated, clean cultivation room conditions, about 95% of water vapor transpired from leaves in the cultivation room is condensed and collected at cooling panels of air conditioners, and then returned to the nutrient solution tank (Kozai, 2013; Kozai et al., 2019a).

4.2.5 Trends in electricity costs

The total electricity costs for the cultivation room with LEDs account for about 20% of the total production costs (with depreciation costs of about 30%, labor costs about 20%, logistics costs about 5%, and costs for other consumables such as fertilizer, water, seeds, CO_2, etc., of about 25%) in Japan where the cost of electricity is relatively high compared to electricity costs in other countries (Ijichi, 2018). When fluorescent lamps were used as the light source prior to the introduction of LEDs, lighting accounted for about 30% of costs.

It should be noted that labor costs, the electricity cost per kWh, and the reliability of the electricity supply vary according to factors such as time, country, region, and season. It must also be noted that the cost of solar panels, wind power generation, and batteries have recently been decreasing relatively rapidly (Kozai, 2018a). In addition, electricity consumption per kg of fresh produce has been decreasing, although around 10 kWh of electricity was required to produce 1 kg of fresh leafy vegetables such as leaf lettuce until 2018.

4.2.6 Mini- and medium-sized PFALs

Fig. 4.3 shows the exterior view of two mini-PFALs without a sanitation room for changing clothes, shoes, etc. As shown in the photo, mini-PFALs look like small windowless warehouses. The external placement of the air conditioning unit (lower left) may have to be changed depending on the climate where the PFAL is located and its purpose of use. The unit can also be placed on the roof or at a height of around 1.5 m rather than on the ground. The air emitted from the outer unit (i.e., condenser) is around 40°C during cooling operation, so the warm air can be used for drying/warming anything by placing it with caution around 1 m from the outer unit.

A mini-PFAL can be placed either inside or outside a building. When a mini-PFAL is placed outdoors under sunlight, a hood or a shade over it may be necessary to avoid heat from strong solar radiation, strong wind/sandstorm, and/or heavy rain/snowfall. When the PFAL is used to produce pesticide- and insect-free transplants, it is covered with an insect screen or placed in an insect-screen net house. In this case, the sanitary room described below is not necessarily required.

A small sanitary room or front room (e.g., 1.5 × 1.5 × 2.5 m) for handwashing and changing from everyday clothing to disinfected or clean clothing needs to be attached to the cultivation room of the mini-PFAL when it is used for the production of vegetables to be served fresh without washing. In this case, the produce is packed in clean bags and then sealed in a clean space such as the cultivation room. If possible, the bags are placed in a heat-insulating box before taking it out from the sanitary room.

Fig. 4.4 shows an exterior view of a medium-sized PFAL with 10 tiers and a daily production capacity of 250 kg (leaf lettuce). The total floor area is about 400 m^2 and the floor area of the cultivation room is about 300 m^2. In addition to the changing room area (3 m by 3 m) in

1.8 m wide, 1.8 m deep, 2.4 m high **3 m wide, 2 m deep, 3 m high, 4 tiers**

FIGURE 4.3 Exterior view of mini-PFALs for personal or family use.

FIGURE 4.4 A medium-sized PFAL with 10 tiers for daily production capacity of 250 kg (leaf lettuce). Total floor area: 404 m^2, Floor area of the cultivation room: 338 m^2. In addition to the changing room area (3 m by 3 m) in the photo, there is another changing room on the opposite side of the PFAL. The annual production per total floor area is (216 kg m^{-2} y^{-1} (= 250 kg d^{-1} x 350 d y^{-1})/404 m^2). *The photo was taken at the Kashiwa-no-ha campus of Chiba University in 2020.*

the photo, there is another changing room on the opposite side of the PFAL. The annual production per total floor area is 216 kg m^{-2} y^{-1} (= 250 kg d^{-1} x 350 d y^{-1})/404 m^2.

4.2.7 Hygiene management of hydroponic cultivation system

Population density of microorganisms is often more than 1000 times higher in the cultivation beds than in the room air because the microorganisms are fed by dead and alive roots, algae, and other organic substances in the cultivation beds (algae grow photosynthetically only under the presence of light, water, and nutrients). Thus, falling down of nutrient solution droplets from the roots to the plant leaves needs to be strictly avoided to keep them clean. Microorganism colony-forming units (CFUs) are generally controlled below 300 per gram of produce fresh weight. No pesticide, insecticide, and bactericide are used during cultivation, so harvests can be used as fresh salad without washing before serving.

The nutrient solution is circulated to minimize amount of drainage in most hydroponic systems. Although sterilization and/or filtering units are placed in the middle of the nutrient solution recirculation pipe, the population density in the cultivation beds is not decreased significantly because a significant portion of the microorganisms and algae tend to stay on the inner surface of the cultivation beds and the roots of plants.

Hygiene management pertains to controlling population densities of unsanitary and/or unpleasant insects, algae, small animals, etc. The invasion of small flying insects, dust, or other foreign substances can be efficiently blocked by keeping the room air pressure slightly (3-5 Pa) higher than outdoor air pressure.

In most hydroponic cultivation systems, inorganic fertilizers only are used to minimize the population density of microorganisms (organic fertilizer is used after its decomposition to inorganic fertilizer through the use of microorganisms in a separate unit). It is desirable to measure and control each of major ion concentrations, although the measurements of PO_4, NH_4^+, etc., using chemical sensors are difficult at present.

4.3 Why is the PFAL necessary?

4.3.1 Use of solar radiation is not free of charge!

A greenhouse is often installed with environmental control units to improve the annual yield and quality of produce and the environment of workers. To use 'free' solar energy, extra initial costs are required for shading screen, thermal screen, insect screen, natural or forced ventilators, units for heating/evaporative-cooling, supplemental lighting, etc. Consumption goods necessary in the greenhouse but unnecessary in the PFAL include oil or natural gas for heating, pesticide/herbicide, etc.

The main reason for these extra initial operation costs aimed at taking advantage of the 'free' solar energy is that the solar radiation (waveband: about 350−2500 nm at sea level) and outside air temperature are often too high or too low depending on the time of day, season, weather, and geographical location. The ever-changing solar radiation and outside air temperature make it difficult to control the greenhouse environment optimally, resulting in variations in the yield and quality of produce.

In addition, only about 50% of solar radiation is photosynthetically active (wavelength: 400−700 nm). Radiation with wavelengths of 700−800 nm is physiologically active (has photomorphological effects) but is photosynthetically inactive, and with 800−2500 nm simply increases the air and leaf temperatures inside the greenhouse.

Therefore, it is reasonable to assume that the cost performance of the PFAL can be higher than that of the greenhouse for selected plant species for a particular purpose of production. This hypothesis has recently been proved for leafy vegetables by researchers and business people in many countries. However, as of 2021, commercial production of fruit vegetables, root vegetables, head vegetables, and medicinal plants is profitable only in a limited number of PFALs. In view of these conditions, there have been efforts to step up PFAL research, development, and business to achieve innovations in PFAL technology considering that: (1) recent advances in smart technology are remarkable, and (2) costs of batteries and electricity generated by natural energy such as solar radiation and wind power have been decreasing.

4.3.2 Comparisons of yield, cost, and cost performance

In general, both the average yield (production per land area) and the initial/operation costs per land area of leafy vegetables in the PFAL are more than 100-fold those of the open field and more than 10-fold those of the greenhouse. Thus, the monetary productivities or cost performances (annual sales divided by annual production costs including depreciation costs) of the PFAL, the greenhouse, and the open field are more or less the same if their unit sales prices per kg of produce are the same (Kozai et al., 2019a). The ratios of annual sales to the initial investment on the PFAL, the greenhouse, and the open field are also more or less the same.

4.3.3 Factors affecting cost performance

In reality, the yield at a given location is considerably affected by the skills of the production manager of the PFAL, the greenhouse, and the open field. The yields in the open field and the greenhouse are also affected by the weather and climate, while the yield in the PFAL is not affected by these factors at all. The high yield in the PFAL is mainly due to: (1) year-round production (longer total cultivation periods per year); (2) use of multitiers; (3) shortened cultivation periods or enhanced growth due to an optimal environment throughout the cultivation period; and (4) no reduction in the yield due to pathogenic diseases, insects, or disastrous weather events such as typhoons (Kozai, 2019; Kozai et al., 2019b). The sales price per kg of PFAL-grown, pesticide-free, and high-quality produce is often 10%–50% higher than that of greenhouse- and open-field-grown produce.

4.3.4 Relative resource consumption per kg of fresh produce

Table 4.1 shows roughly estimated relative resource consumption of components per kg of produce of the PFAL compared to consumption by the greenhouse and the open field (Kozai, 2018b, 2019).

The total production cost per kg of produce, C_T, is expressed by the total sum of a product of the consumed resource component 'i' for 1 kg of produce, Q_i, and the unit cost of resource component 'i', C_i. Namely, $C_T = \Sigma(Q_i \times C_i)$ (i = 1–10). The productivity or the cost performance is expressed by Y/C_T where Y is the yield (see Chapters 12 and 13). The resource consumption of the respective components per kg of produce needs to be estimated for the particular product, location, season, etc., when this method is applied.

TABLE 4.1 Rough estimation of the relative resource consumption of components per kg of produce of a PFAL compared to consumption by a heated greenhouse with soil cultivation and an open field with irrigation and agricultural machinery. The values relative to the PFAL are estimated based on the author's knowledge, experience, and presumptions. For the relative values of fossil fuel and pesticides/herbicides, the reference value of 1 is assumed for the open field.

I	Resource component	PFAL	Greenhouse	Open field
1	Land area	1	10	100
2	Water	1	20	30
3	Fertilizer	1	2	2
4	Working hours	1	2	1
5	Electricity	1	0.01	0
6	CO_2	1	0	0
7	Fossil fuel	0	100	1
8	Seeds	1	1.2	1.4
9	Pesticide/herbicide	0	1	1
10	Others	1	1	0.5

(1) Land area: Annual yield (production per land area) of the PFAL with 10 tiers is roughly 10-fold and 100-fold that of the greenhouse and the open field, respectively, in a temperate climate area (Kozai et al., 2019a). In other word, land area required for production of 1 ton of plants by the PFAL is about 1/100th compared to open fields, and 1/10th compared to greenhouses. Thus, we need '1 ha of PFAL' only instead of 100 ha of open field for vegetable production.

(2) Water for irrigation: About 95% of transpired water vapor from leaves is recycled for irrigation in the PFAL (Chapter 8). This reduction in water consumption is a significant advantage of the PFAL over the greenhouse and open field where the available water is scarce and/or the water quality is not suitable for irrigation. Furthermore, a significant portion of irrigated water is evaporated from the soil surface and/or drained from the soil of greenhouse and the open field, while the amount of such water loss in the PFAL can be minimized. An extra amount of water is required in a greenhouse with an evaporative cooling unit.

(3) Water for washing/cleaning: Water consumption for washing the PFAL-grown produce before cooking or service is less than 1/10th compared to greenhouse- and open-field-grown vegetables because PFAL-grown vegetables are clean (free from pesticide, insects, and other foreign substances), and the population density of microorganisms on leaves is 1/1000th to 1/100th of field-grown vegetables.

(4) Fertilizer: With use of hydroponic cultivation system in the PFAL, application amount of P/N/K fertilizer per kg of produce is reduced by more than half compared to open field. In the greenhouse and the open field, both organic and inorganic fertilizers can be used. On the other hand, around 50% of fertilizer is often leached/drained away and/or adsorbed to the soil in the greenhouse and the open field.

(5) Working hours: The distance traveled on foot and by vehicle per kg of produce of workers is much shorter with the PFAL than with the greenhouse and the open field. Working hours per kg of produce are assumed to be shorter in the open field than in the greenhouse since vehicles are used for the most part in various operations in the open field.

(6) Electricity: Electricity is mostly consumed for lighting and air conditioning in the PFAL. In the greenhouse, electricity is used mainly for ventilation, pumping, heating/cooling, and battery-driven vehicles. All machines/vehicles are driven using electricity only both in the PFAL and greenhouse. Battery-driven agricultural machines are used in some cases in the open field.

(7) CO_2: In most cases, pure liquid CO_2 contained in a high-pressure cylinder-type container (30–70 kg of CO_2; 0.5–0.8 US$ per kg in Japan) is supplied during the photoperiod in the PFAL to keep its concentration at around 1000 $\mu mol\ mol^{-1}$ to promote photosynthesis and thus the growth of plants. Only about 10% of CO_2 is released to the outside in the fairly airtight PFAL, while about 50%–60% of CO_2 is released to the outside through air gaps of a CO_2-enriched greenhouse with all windows closed. CO_2 is free of charge in the open field but its concentration is always around 400 $\mu mol\ mol^{-1}$. CO_2 is a by-product obtained from a chemical plant using fossil fuel. CO_2 is also a by-product of the respiration of living organisms, so CO_2 produced by fungus/microorganisms, fish, animal/livestock, humans, etc., can be used as a CO_2 source for plant photosynthesis if it is collected efficiently.

4.4 Sustainable development goals

4.4.1 Goal 1: end poverty in all its forms everywhere

A PFAL with a hydroponic cultivation system can be built and used efficiently anywhere in the world—in hot, cold, dry, and wet regions with nonfertile soils—to produce high-quality functional plants such as leaf lettuce plants and herbs such as basil all year round, as well as for producing high-quality transplants (seedlings, micropropagated plantlets, and grafted transplants) regardless of weather, using minimum land/floor area and other resources such as water and fertilizer.

Over the past decade there have been various initiatives to commercially produce in PFALs root vegetables such as mini-carrots, mini-turnips, and mini-radishes; fruit vegetables such as strawberries and cherry tomatoes; and some medicinal plants and ornamental plants but only a limited number of PFALs are currently making a profit as of 2021. Staple crops such as wheat, rice, and maize can also be grown in PFALs relatively easily for research, educational, and recreational purposes, but the cost performance (ratio of its economic value of produce to production costs) for these is too low to be economical and practical.

Nonprofit or public-supported microfinancing organizations could lease to farmers and other interested parties mini-PFALs with a floor area of 3–20 m^2 or funds to rent mini-PFALs to start a small personal, family, or group business to help end poverty. The annual yield of leaf lettuce in a mini-PFAL with four tiers is about 85 kg m^{-2} (floor area) y^{-1} and 213 kg m^{-2} y^{-1} (= 85 kg m^{-2} y^{-1} x 10/4) in a PFAL with 10 tiers if operated by a skillful professional grower, regardless of the weather; however, the yield would probably be around 10–20 kg m^{-2} if operated by a beginner. Thus, well-organized, remote on-site training is essential for improving skills in PFAL management.

The initial investment cost of a PFAL per unit floor area is about 10 times higher than that of a greenhouse with environment control units, and is around 100 times higher than that of an open field equipped with irrigation systems and standard cultivation machinery. However, the initial investment cost per kg of produce for PFAL, greenhouse, and open field is almost the same because the average annual yield per unit land area of the PFAL is around 10-fold and 100-fold higher than the greenhouse and the open field, respectively.

The basic unit of a scalable PFAL is called a cultivation system module (CSM), with a floor area of around 10–2100 m^2 (Kozai, 2018a). Using multiple CSMs, a PFAL can be scaled up to any size. This scalable characteristic using CSMs without any extra costs for scaling up can play an important role in ending poverty and improving income by increasing production capacity every 1–3 years.

4.4.2 Goal 2: end hunger, achieve food security and improved nutrition, and promote sustainable agriculture

The mini-PFAL operated by electricity generated from renewable energy can be a sustainable plant production system contributing to ending hunger, achieving food security, and improving the nutrition of people. Operation and maintenance manuals and other necessary information on the mini-PFAL can be downloaded from an open database and a self-learning system via the Internet. The mini-PFAL can be used as a small private/family business or for

In the open field, solar light energy is often too abundant or too scarce for plant growth, CO_2 concentration at daytime (about 400 μmol mol^{-1}) is always too low to maximize the photosynthesis and thus plant growth, and the air/soil temperatures are often too low and/or too high, so that the annual average of light energy use efficiency of plants is much lower than that of PFAL-grown plants (Kozai, 2011). Furthermore, risks of plant damage due to drought, strong winds, and/or rain, and the spread of pest insects are high in open fields. The PFAL's protection of plants from these hazards is also beneficial for human physical and mental health.

Dry air in the Earth's atmosphere contains 78.1% nitrogen (by volume), 21% (or 210,000 μmol mol^{-1}) oxygen, 0.04% (or 400 μmol mol^{-1}) CO_2, and small amounts of other gases. The atmospheric air also contains a variable amount of water vapor, on average around 1% at sea level. It should be noted that the low concentration of CO_2, sole carbon source of plants, is one of the key limiting factors in photosynthesis (Taiz and Zeiger, 2006). In the airtight PFAL containing plants, the CO_2 concentration in the room air during the photoperiod decreases to around 100 μmol mol^{-1} within 1 h or so if CO_2 supply is stopped. This is why CO_2 gas needs to be supplied continuously during the photoperiod in the PFAL. In this sense, the PFAL is a CO_2-absorbing system.

4.4.8 Goal 8: promote sustained, inclusive, and sustainable economic growth, full and productive employment, and decent work

The productivity of advanced PFALs will more than double that of existing PFALs by 2030 (Kozai, 2018a, 2019) and will make a substantial contribution to employment and economic growth. It is expected that people who want to start a small business can rent a mini-PFAL and build it on a limited unfertile and/or contaminated land area with a shortage of irrigation water for producing and selling fresh vegetables, medicinal plants, and various seedlings as cash crops. Since some recent PFALs are designed to be scalable, it will be possible to expand their production capacity easily year after year (Kozai, 2018a).

As of 2021, leafy vegetables and seedlings for greenhouse production are produced in most commercial PFALs. However, a few PFALs for commercial production of fruit vegetables such as cherry tomato plants exist (see Chapter 23), and the number of PFALs or commercial production of strawberry and medicinal plants will increase significantly in the 2020s.

4.4.9 Goal 9: build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation

PFALs can be reinforced to construct a resilient infrastructure in a local area. The infrastructure is strengthened more through integration with other systems such as wastewater treatment, bio-waste treatment, electric power supply with use of natural energy, CO_2, and heat energy recovery/delivery, all of which promote inclusive and sustainable industrialization and agriculture. Food mileage and food loss are also minimized, and food security is strengthened when fresh vegetables are produced in the consumption area.

An advantage of the PFAL built in residential and industrial areas is that the peak time zone of electricity consumption for lighting and cooling for the PFALs occurs between handling, and prolongs shelf life due to the cleanness (low microorganism population in produce) and less physical damage of produce. Local people tend to try to minimize vegetable and food waste when they know who, how, and where they are produced. In the PFAL, historical and cultural cultivars can be produced without any technical difficulty for local people.

Since the PFAL is thermally well insulated and highly airtight and the plant environment is controlled as desired, use efficiencies of electricity, water, fertilizer, and CO_2 are much higher than those in the greenhouse and open field (see Kozai (2013); and Chapter 8 of this book). In addition, waste heat energy generated mainly by lamps and transferred to the outer units (or condensers) of air conditioners can be efficiently used for drying the plant residue or other wet substances at around 40°C, thereby improving hygienic conditions and mitigating food security risks such as local hazardous weather, pest insects, animals, and human crimes.

4.4.13 Goal 13: take urgent action to combat climate change and its impacts

The PFAL will reduce the negative impact of climate change on plant productivity. The plants growing in the PFAL are almost completely protected against strong wind, heavy rain, flood, drought, hail/snow, extreme temperatures, insects, animals, and thieves because the PFAL is airtight and thermally insulated and all the doors can be locked. CO_2 emissions per kg of PFAL-grown produce due to electricity generation and fertilizer manufacturing have been reduced in recent years and will be further reduced in the near future. The consumption of water and fertilizer per kg of produce in the PFAL has already been significantly reduced compared with consumption in the greenhouse and open field.

On the other hand, the CO_2 emitted during the manufacturing of iron, cement, and aluminum used as structural components of the PFALs needs to be reduced. Likewise, the plant residue produced in PFALs as waste needs to be reduced and/or recycled on-site. Reinforced wooden structural components need to be used more for the PFAL building and cultivation racks (Kikuchi and Kanematsu, 2019). Biodegradable plastics and paper bags also need to be used more in cultivation trays and panels.

4.4.14 Goal 14: conserve and sustainably use the oceans, seas, and marine resources for sustainable development

PFALs constructed under water or underground can be more sustainable than those built above ground. PFALs can also be built on ships for providing fresh vegetables to people on board. Besides, closed-type inland aquaculture systems for producing ocean fish constructed near or in urban areas are becoming more and more resource efficient (in terms of water, electricity, feed, and labor) recently. Thus, this type of aquaculture system using food waste produced in urban areas as feed will contribute to the conservation and sustainable use of the oceans, seas, and marine resources.

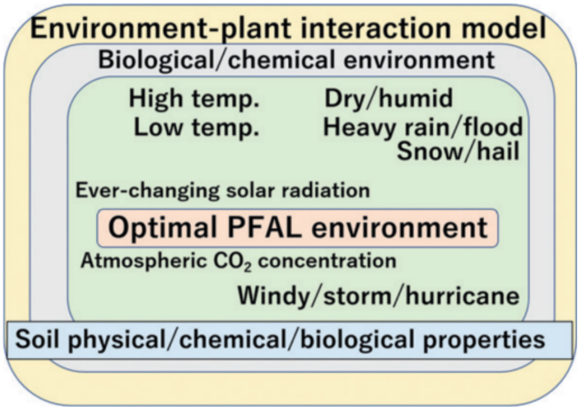

FIGURE 4.7 Learning the functions of an ecosystem starting with the PFAL ecosystem, the simplest one, to more complex ecosystems such greenhouse, open field, and nature ecosystems.

4.6 Conclusion

Achieving the SDGs is a challenge for all people living on this planet, especially after the COVID-19, a recent pandemic. Furthermore, there are so many ideas, tools, methods, systems, and collaborative approaches for contributing to the achievement of the SDGs. The PFAL is just one of them. However, PFALs that are properly applied in the various ways discussed in this chapter have enormous potential in contributing to the SDGs. The descriptions in this chapter largely center on the author's limited experience with and theoretical consideration of PFALs constructed in relatively large cities. Therefore, some adjustments would be necessary for the efficient use of PFALs in a rural or a remote area. Achieving the SDGs by 2030 will help us achieve the next mission of establishing technology and innovative ways of thinking to nourish over 9 billion people and enable them to live meaningful lives on this planet in 2050 with minimum consumption of resources and minimum emission of environmental pollutants (Lee, 2019).

PFAL technology using LEDs emerged around 2000 and is still in its infancy. It is only recently that efforts to apply PFAL technology to achieve the SDGs have started in earnest. Therefore, many promising initiatives to achieve the SDGs through the introduction of PFALs can be expected in the future.

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It is noteworthy that candela [cd] is the distinctive unit in the SI base units because it is related to a physical quantity of radiant intensity [W sr^{-1}] through a photobiological/physiological weighting factor: spectral luminous efficacy for photopic vision.

5.2.4.2 *SI derived units*

The SI derived units are defined as products of powers (including negative powers) of the SI base units. That is to say, the SI derived units are units constructed by multiplying, dividing, or powering the SI base units in various combinations. The set of the SI base units and SI derived units is designated as the set of coherent SI units. In this regard, we can find a similar term, a "complete" set of SI units, in the SI Brochure. The complete set of SI units includes both the set of coherent SI units and the multiples and submultiples formed using the SI prefixes (described later).

(1) SI derived units expressed in terms of the SI base units

Examples of the SI derived units expressed in terms of SI base units include: [m^2] (area), [m s^{-1}] (speed, velocity), [A m^{-1}] (magnetic field strength), [mol m^{-3}] (amount of substance concentration), and [cd m^{-2}] (luminance).

(2) SI derived units with special names and symbols

Twenty-two units of the SI derived units are assigned special names and symbols. Together with the seven SI base units, they form the core of the set of coherent SI units. All other SI units of the complete set of SI units are combinations of these 29 units.

Examples of the 22 SI derived units include the following: radian [rad] (plane angle), steradian [sr] (solid angle), hertz [Hz] (frequency), newton [N] (force), pascal [Pa] (pressure), joule [J] (energy, work), watt [W] (power, radiant flux), volt [V] (electric potential difference), siemens [S] (electric conductance), degree Celsius [°C] (Celsius temperature), lumen [lm] (luminous flux), and lux [lx] (illuminance).

It is noteworthy that one radian is the angle subtended at the center of a circle by an arc that is of equal length to the radius (entire plane angle: 360 degrees = 2π rad). One steradian is the solid angle subtended at the center of a sphere by an area of the surface that is equal to the squared radius (entire solid angle: 4π sr) (Fig. 5.1). As the units for the plane and solid angles are [rad] = [m m^{-1}] and [sr] = [m^2 m^{-2}], respectively, the unit for both quantities can be expressed as 1. However, unit symbol 1 is not shown explicitly.

The numerical value of a temperature difference or temperature interval is the same when expressed in either degrees Celsius or in kelvin because the relationship of Celsius temperature t [°C] and thermodynamic temperature T [K] is given as t [°C] = T [K] − 273.15 [K]. The temperature of 273.15 K is the freezing point of water. The unit of thermodynamic temperature (1 K) is given as 1/273.16 of the triple point temperature of water (273.16 K). The triple point temperature of a substance is the temperature at which the three phases (gas, liquid, and solid) of that substance in a single-component system coexist in thermodynamic equilibrium.

5.2.4.3 *SI prefixes for expressing decimal multiples and submultiples of SI units*

SI prefixes are the prefixes provided to express decimal multiples and submultiples ranging from 10^{24} to 10^{-24} for use with SI units. In fields related to plant sciences and

Terminology definitions are mostly quoted from International Electrotechnical Commission (IEC) 60050-845-01 (1987). Several terms associated with photonmetric quantities are also explained using illustrations and graphs. Several parts of this section include partially reconstituted and modified contents of the author's earlier works (Fujiwara, 2013, 2016, 2019).

5.3.2 Fundamental radiometric, photometric, and photonmetric quantities with their SI units

The author selected four radiometric quantities as fundamental ones: radiant intensity, radiant flux, radiant energy, and irradiance. Those quantities are placed along with their SI units in the second-left column. Then photometric and photonmetric quantities with their associated units are put in the right columns so that the relations among the quantities and SI units can be readily understood (Table 5.5). Relational expressions among the quantities in the same law are provided in the leftmost column to indicate quantitative relations. Quantities in the same row are mutually equivalent in a metric sense.

The following definition in the first sentence for each term, except for "photon flux density," is a direct quote from International Electrotechnical Commission (IEC) 60050-845-01 (1987) in which the term definitions are presented clearly. Quantity symbols and equations

TABLE 5.5 Fundamental radiometric, photometric, and photonmetric quantities with their SI units.

Quantitative relations	Radiometric quantities	Photometric quantities	Photonmetric quantities
A	radiant intensity	luminous intensity	photon intensity
	$[\mathrm{W\ sr^{-1}}]$	[cd]	$[\mathrm{mol\ s^{-1}\ sr^{-1}}]$
$A \times 1\ \mathrm{sr}$	radiant flux	luminous flux	photon flux
$= B$	$[(\mathrm{W\ sr^{-1}})\ \mathrm{sr}]$	[cd sr]	$[(\mathrm{mol\ s^{-1}\ sr^{-1}})\ \mathrm{sr}]$
	= [W]	= [lm]	= $[\mathrm{mol\ s^{-1}}]$
$A \times 1\ \mathrm{sr} \times 1\ \mathrm{s}$	radiant energy	quantity of light	photon number
$= B \times 1\ \mathrm{s}$	[W s]		$[(\mathrm{mol\ s^{-1}})\ \mathrm{s}]$
	= [J]	[lm s]	= [mol]
$A \times 1\ \mathrm{sr} \times 1\ \mathrm{m^{-2}}$	irradiance	illuminance	photon flux density
$= B \times 1\ \mathrm{m^{-2}}$			(photon irradiance)
		$[\mathrm{lm\ m^{-2}}]$	$[(\mathrm{mol\ s^{-1}})\ \mathrm{m^{-2}}]$
	$[\mathrm{W\ m^{-2}}]$	= [lx]	= $[\mathrm{mol\ m^{-2}\ s^{-1}}]$

A and B, respectively, denote quantity symbols representing quantities for the intensities in the first row and fluxes in the second row.

Modified from Fujiwara, K., 2013. Fundamentals of light on plant cultivation and LED light irradiation technology. Refrigeration 88, 163–168. (in Japanese); Fujiwara, K., 2016. Radiometric, photometric and photonmetric quantities and their units. In: Kozai, T., Fujiwara, K., and Runkle, E. (eds.) LED Lighting for Urban Agriculture, Springer Science+Business Media Singapore, p. 367–376; Fujiwara, K., 2019. Light sources. In: Kozai, T., Niu, G., and Takagaki, M. (eds.) Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production, second ed., Academic Press, London, UK, p. 139–151.

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Note: 'Page numbers followed by "f" indicate figures and "t" indicate tables.'