CHAPTER

PFAL BUSINESS AND R&D IN THE WORLD: CURRENT STATUS AND PERSPECTIVES

3

INTRODUCTION

This chapter describes the history, current status, and perspectives of plant factories with artificial lighting (PFAL) in Japan, Taiwan, China, North America, and Europe (England and The Netherlands), including research, development, and business. The governmental subsidy for PFAL research and development (R&D) and business in Japan are introduced. Taiwanese companies have started to export and build turn-key PFALs abroad. The Chinese Academy of Agricultural Sciences started a national project on intelligent plant factory production technology in 2013 supported by the Ministry of Science and Technology, and the project was joined by 15 universities, institutes, and private companies. In Korea, the Ministry of Knowledge Economy (MKE) started a research project named “Development of major components for IT-LED based plant factories” in 2009. The annual domestic market of the PFAL business in Korea is worth nearly US$600 million. In the USA, several large-scale commercial facilities were recently built to produce pharmaceutical protein products (antigens and antibodies). More recently, large commercial PFAL facilities were built close to large cities such as Chicago. In The Netherlands, two relatively large PFALs were built in 2014 and 2015 for research and development by private companies, aiming to commercialize PFALs on a large scale. The perspectives of the PFAL business and R&D in the world are discussed.

JAPAN

Toyoki Kozai

Japan Plant Factory Association, c/o Center for Environment, Health and Field Sciences, Chiba University, Kashiwa, Chiba, Japan

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

BRIEF HISTORY AND CURRENT STATUS OF PFAL BUSINESS

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

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

In the late 1990s, fluorescent lamps became preferred mainly due to their higher PAR (photosynthetically active radiation; wavelength, 400–700 nm) output per watt. Then, PFALs consisting of multi-tiers (4–15 racks) with a vertical separation of about 40 cm between tiers became available. PFALs using LEDs as their light sources began to be commercialized in 2005 in Japan.

As of March 2014, the number of PFALs used for commercial production was 165 and is estimated to exceed 200 by the end of 2014 in Japan, and the number will continue to increase in 2015 and beyond. There were 34 PFALs in March 2009, 64 in March 2011, 106 in March 2012, and 125 in March 2013. In addition, closed plant production systems with artificial lighting (CPPS) units with a floor area of 16.2 m^2 for transplant (seedlings and plantlets from cuttings) production were in commercial use in 2014 at around 300 locations throughout Japan, and some in Australia and China (see Chapter 19, Section 1).

The largest PFAL with fluorescent lamps, which is operated by Spread Co., Ltd. in Kyoto, produces 23,000 leaf lettuce heads daily (see Chapter 26, Section 2). A PFAL with all LEDs producing 10,000 leaf lettuce heads daily was built by Mirai Co., Ltd. in Tagajoh, Miyagi Prefecture in March 2014 (see Chapter 26, Section 3). Figure 3.1 shows the PFAL with 3000 fluorescent lamps (each 1.2 m long) built in June 2011 at Kashiwa-no-ha Campus, Chiba University, operated by Mirai Co., Ltd. On the same campus, a new PFAL was built in September 2014 by Japan Dome House Co., Ltd. (see Chapter 26, Section 4). In the campus of Osaka Prefecture University, a PFAL with all LEDs was built in September 2014, which can produce 5000 leafy greens daily (see Chapter 23).

FIGURE 3.1

PFAL at Chiba University built in 2010, operated by Mirai, Co., Ltd. Total floor area: 406 m^2; Floor area of culture room: 338 m^2, 10 tiers, nine rows. Mainly leaf lettuce and Romaine lettuce. 3000 heads per day (1 million heads/year or 2800 heads/m^2/year).

The size of the current PFAL business market is still very limited, and was probably worth about 12 billion yen (1 US$ = 120 yen) in 2014. According to a survey by the Ministry of Agriculture, Forestry and Fisheries (MAFF) published in March 2014, (1) 75% of PFALs are operated by private companies (the rest are operated mostly by incorporated agricultural organizations); (2) 55% of PFALs have a floor area of less than 1000 m^2 including the operation room and office; (3) 75% of PFALs have annual sales of less than 50 million yen; (4) 75% of PFALs use fluorescent lamps as the light source; and (5) 35% of PFALs received both a subsidy and loan, 30% received neither subsidy nor loan, 20% received a loan, and 15% did not answer. The initial and operation costs are given in Chapter 2, Section 6.

RESEARCH AND DEVELOPMENT

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

In 2000, a CPPS was built for R&D at Matsudo Campus, Chiba University (Kubota and Chun, 2000; Chun and Kozai, 2001) (Figures 3.2 and 3.3). This PFAL was designed and operated based on the concept of the CPPS (Kozai and Chun, 2002; Kozai et al., 2006). In this PFAL, handling of culture plug trays and operation of the precision irrigation system were automated (Ohyama et al., 2005). Using the PFAL, the production of disease-free sweet potato transplants, tomato seedlings, and medicinal plants were studied (Afreen et al., 2005, 2006; Zobayed et al., 2006, 2007) (Figure 3.4).

FIGURE 3.2

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

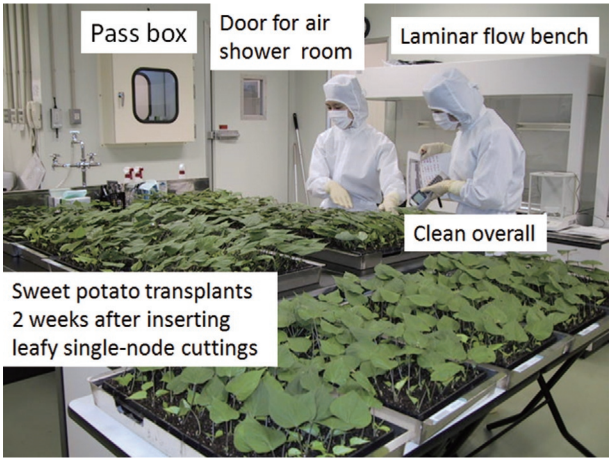


FIGURE 3.3

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

FIGURE 3.4

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

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

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

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

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

In March 2011, the Great East Japan Earthquake struck the northeastern coast of the main island of Japan, and the ensuing tsunami hit the Pacific coast of Fukushima, Miyagi, and Iwate prefectures (destroying three nuclear power plant units in Fukushima). Since agriculture and horticulture are important industries in those areas, the Japanese government provided subsidies to build new greenhouses and PFALs in 2012 and 2013.

In November 2014, the International Plant Factory Conference was held in Kyoto and Osaka attracting 160 participants including 60 overseas participants (http://www.shita.jp/ICPF2014/).

PUBLIC SERVICE

In June 2010, the Japan Plant Factory Association (JPFA), a nonprofit organization, was established in the Kashiwa-no-ha campus of Chiba University. The number of JPFA corporate members was 60 in 2010 and 98 in 2014. JPFA has two roles: one is collaboration with Chiba University and the other is collaboration with national and international organizations, offering monthly half-day seminars, monthly 2- or 3-day training courses, consulting services, guided tours for visitors to the campus, and collaborative R&D with the corporate member companies (see Chapter 25). In 2012, an association for PFAL managers was newly established, consisting of 58 corporate members and having its office within the JPFA's office.

There are several exhibitions and conferences related to the PFAL business, including: (1) Agro-innovation held at Tokyo Big Sight every year (http://www.jma.or.jp/ai/en/) organized by the Japan Management Organization and (2) Greenhouse Horticulture & Plant Factory Exhibition/Conference held at Tokyo Big Sight every 2 years (http://www.gpec.jp/english/) supported by the Japan Greenhouse Horticulture Association.

TAIWAN

Wei Fang

Department of Bio-Industrial Mechatronics Engineering, National Taiwan University, Taipei, Taiwan

STATUS OF PFAL IN TAIWAN

Whereas the global population will increase from 7 to 9.6 billion in less than 40 years, Taiwan's population is shrinking. It is also estimated that 70% of the global population will live in cities compared with the current 50% (Kozai, 2014), and the trend is the same in Taiwan. As a result, urban agriculture will increase, and so PFALs will play an important role. As mentioned by Glaeser

(2011), cities should develop upwards not outwards, and the same is true for urban agriculture: PFALs are the answer. Many people in Taiwan agree, and consider that PFALs can make us richer, smarter, greener, healthier, and happier.

There are 45 organizations engaged in leafy green production using PFALs in Taiwan as of September 2014, and 56 PFALs of various sizes have been built and operated in the last 4 years. Among these 45 organizations, there are 2 research institutes, 4 universities, and 39 private companies involved, as shown in Figure 3.5. The PFALs built by universities and research institutes are financially supported by their own funds and from the government; the government provides no support to private companies.

Among those 56 PFALs, 73%, 20%, and 7% are located in northern, central, and southern Taiwan, respectively, as shown in Figure 3.6. The scale of PFALs is shown in Figure 3.7: they are categorized into six sizes based on the amount harvested daily, assuming a cropping density of 25 plants per square meter of culture bed. In between the smallest (<100 plants/day) and the largest (>10,000), the size categories are 100–500, 500–1000, 1000–5000 and 5000–10,000. Half of all PFALs are small with daily production of less than 100 plants and only one PFAL with daily production of more than 10,000 plants, which is probably the world's largest PFAL with daily production of 60,000 plants (2.5 tons of leafy greens). Over 90% of PFALs are located in one room on one floor of an office building, typically on an empty floor or basement inside a building in an industrial park in the Taipei area.

Some companies have started to export and build turnkey PFALs abroad, mainly in China as shown in Figure 3.8. To date, there have been 11 such projects, of which two have not been completed (shown by dashed line), one in Beijing and one in Xiamen. These two were suspended due to financial reasons. In 3 out of the 11 projects, the company built the PFAL in its own branch located in China.

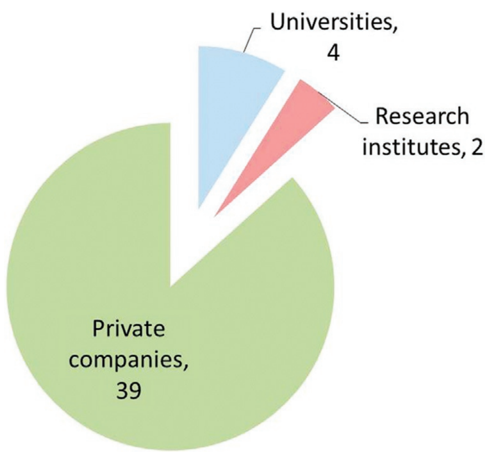


FIGURE 3.5

Distribution of PFALs in Taiwan categorized by organization before September 2014.

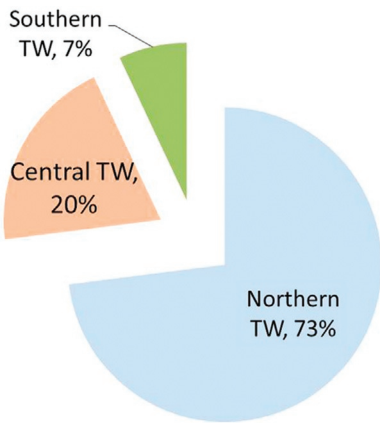


FIGURE 3.6

Geographical distribution of PFALs in Taiwan before September 2014.

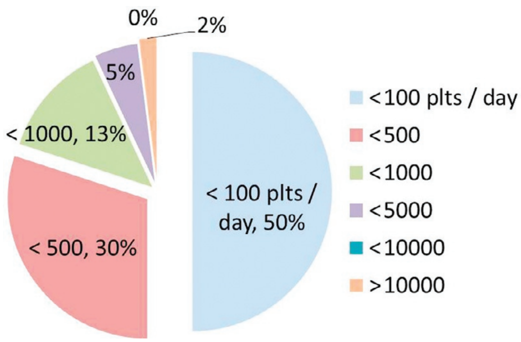


FIGURE 3.7

Number of PFALs in Taiwan categorized by daily production before September 2014.

PFAL EXPO IN TAIWAN

To promote PFALs, various technical books have been translated (Kozai, 2009, 2012; Takatsuji, 2007; Fang, 2011a,c, 2012), and booklets for the general public (Fang, 2011b; Fang and Chen, 2014) have been written. Exhibitions and conferences have been held by the Photonics Industry & Technology Development Association (PIDA) of Taiwan. PIDA has held a photonics festival in Taipei for 23 consecutive years. It is an NPO established by the Taiwan Government to assist the country's optoelectronics industry. Apart from serving as an exhibition organizer, they also provide services such as industry research, consulting, promotion, and communication in the industry and market. 2014 was the third year in which they included PFALs within the festival. Another two NPOs, the Taiwan Plant Factory Industrial Development Association (TPFIDA, founded in 2011) and the Chung-hwa Plant

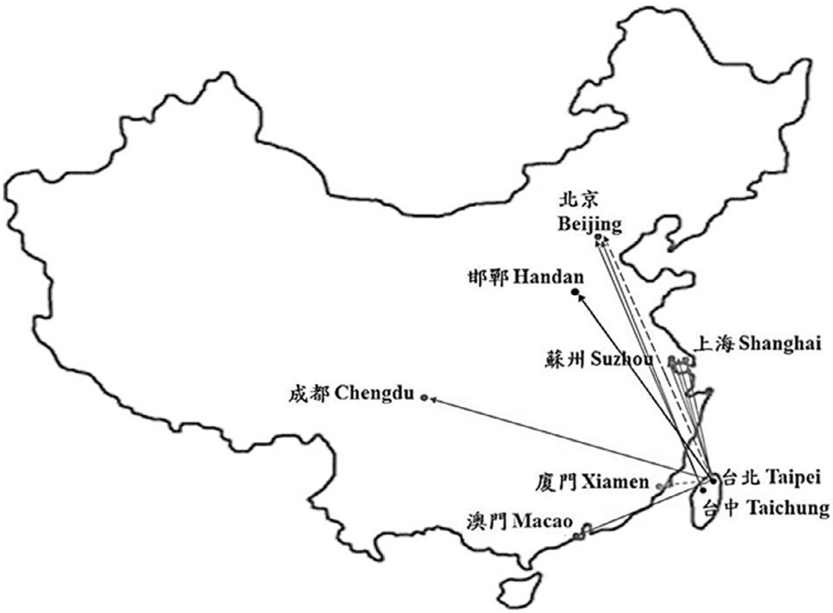


FIGURE 3.8

Export of turnkey PFALs from Taiwan to China.

Factory Association (CPFA, founded in 2012), were major co-organizers. The number of booths related to PFALs increased from 36 in 2012 to 108 in 2014.

Among the PFAL booths of the 2014 Expo, most of the companies demonstrated hardware used in PFALs. Several of them exhibited various spectrums and controls of LED tubes and panels, while others showed locally developed or imported nutrient control systems. One booth was that of Mirai Co., Ltd., Japan, which showed its PFAL turnkey capabilities. Also, several local companies promoted their ability to set up PFALs abroad. At least five companies demonstrated home appliance-style plant growth desktop devices and three showed growth benches for shops, restaurants, and supermarkets with or without environmental control capability. One company showed an LED illuminated green wall that cleans the air, another exhibited an aquaponics system, and another showed various by-products from PFAL-grown vegetable ingredients.

PFAL RESEARCH

Cost comparison of PFALs

Crops grown in PFALs can be classified into four types: RTC (ready to cook), RTE (ready to eat), CAW (cook after wash), and EAW (eat after wash). The retail price of RTE lettuce and CAW Pak-Choi varies widely, from NT$500 to 2000 and from NT$200 to 300 per kg (1 USD = 31.46 TWD), respectively. Table 3.1 shows the average retail price and cost of lettuce produced in PFALs in Japan and Taiwan with the same daily production of 1000 plants.

Table 3.1 Comparison of Retail Price and Cost of Lettuce Produced in PFALs in Japan and Taiwan

Lettuce	Japan	Taiwan
Retail price[a]	¥150～200	¥81～420[b]
Cost[a]	¥80～100	¥47～56[b]

[a]*Japanese yen per 70 g fresh mass produced.*
[b]*Exchange rate at 1 NT$=3 Japanese yen.*

There are some fundamental reasons for this dramatic difference in production cost. In particular, the high cost of construction and equipment, especially LEDs, leads to high depreciation cost, while the high cost of labor and electricity leads to high operating cost.

Spectra of LEDs used in PFALs

Figure 3.9 shows spectra of artificial light used in PFALs in Taiwan. Assuming the same size of culture bed (1.8 × 1.2 m), the light efficiency of various lights is compared in Table 3.2. The row with the shaded background shows that LED panels are less efficient than LED tubes with reflective film between the tubes. Also, the longer the tube, the higher the overall quantitative efficiency measured in micro-mole per joule.

Wireless sensor networks in PFALs

A wireless sensor network (WSN) is used to evaluate the uniformity of air temperature, humidity, and light intensity horizontally in a layer and vertically within layers of a PFAL (Chang et al., 2011; Juo et al., 2012). Each wireless sensor module is equipped with temperature, relative humidity, and light sensors, hanging from the tops of crops in each layer of culture beds to measure the uniformity of distribution of light and air. As shown in Figure 3.10, the temperature distribution is clearly related to the distribution of the fresh weight harvested. This means that greater uniformity of temperature reduces the variation in final fresh weight, and so a smart fan system has been developed to increase the uniformity (Lee et al., 2013).

Ion-selective sensors for nutrient detection

Traditional ion-selective sensors are expensive and have a short usable lifespan. New ion-selective sensors for detecting macro-elements in nutrient solutions have been developed. Figure 3.11 shows the sensing responses of screen-printed ion-selective electrodes (ISEs) for Ca^{2+}, K^{+}, Mg^{2+}, NH^{4+}, and NO^{3-}.

Nondestructive plant growth measurement system

A measurement system with cameras attached to a sliding rail on each layer of the culture bed accompanied by weighing devices for each plant was developed for continuous and automatic measurement of plant growth. The system takes images at preset time intervals and stitches all images across the culture bed to form a panoramic image of the entire bed using a computer with image-processing capability. In the recording process, the cameras move across the whole culture bed and capture images. Temperature and humidity sensors are also integrated with the imaging system to acquire

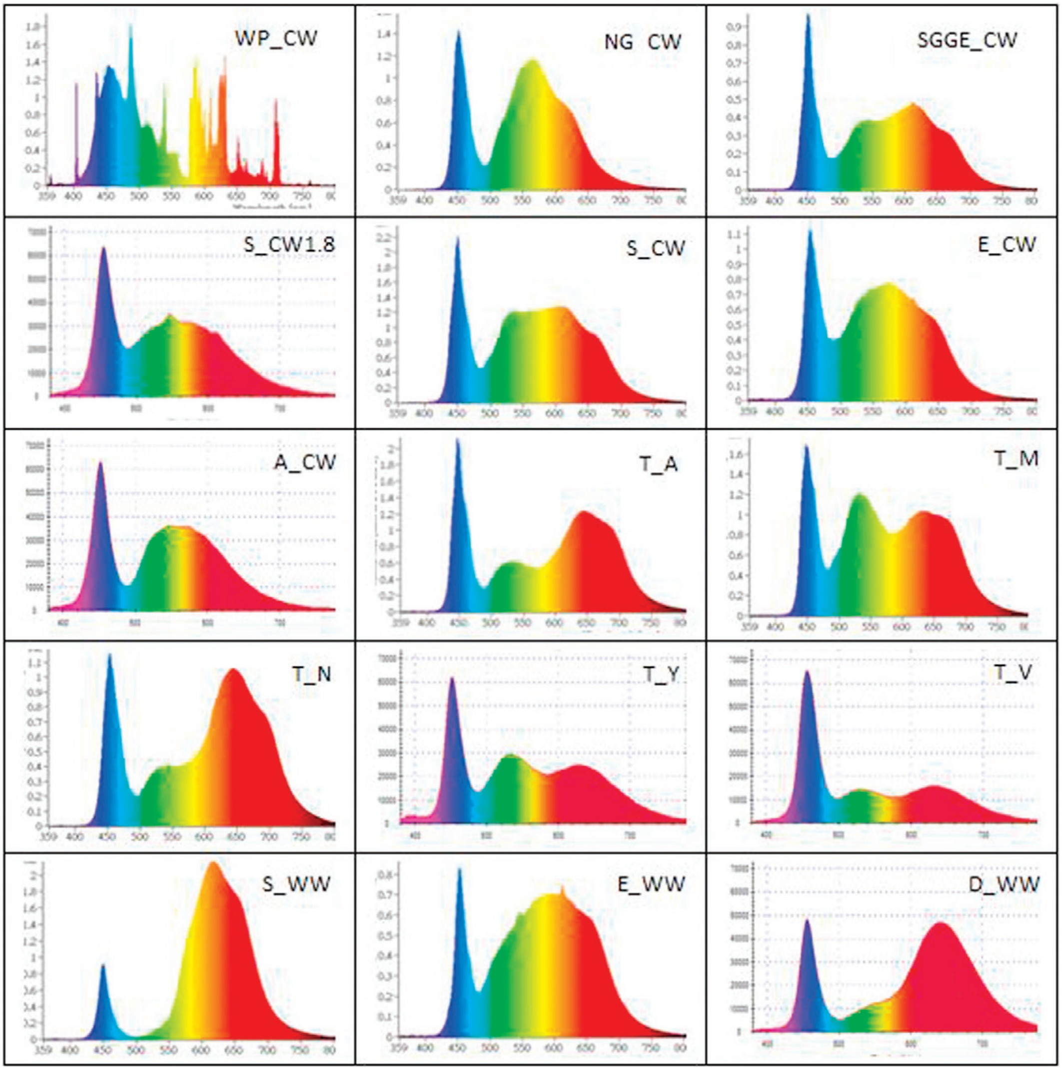


FIGURE 3.9

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

spatial-temporal environmental information during the plant growth period. The image-processing algorithms, which calculate geometric features such as projected leaf area, plant height, volume and diameter, have been developed and incorporated into the automated measurement system (Yeh et al., 2014). The accompanying automatic weighing system using load cells was also developed to record the fresh weight of individual plants throughout the growth period. The weighing system

Table 3.2 Comparison of Efficiency of Various Light Sources Used in PFALs (Fang, 2014)

Comp_Spec of Light Sources	Reflectors on Top	No. of Tubes or Panels	PPF[a] $\mu mol\ m^{-2}\ s^{-1}$	PPF × Area[b] $\mu mol\ s^{-1}$	Power Consumption, W	Efficiency, $\mu mol\ J^{-1}$
S_CW1.8	Y	6 Tubes	334.9 ± 86.6	723.4	172.97	4.2
T_V	Y	9 Tubes	281.6 ± 59.4	608.4	195	3.1
H_CW	Y	9 Tubes	273.9 ± 79.8	73.9	212	3.1
T_A	Y	9 Tubes	225.8 ± 49.1	487.8	189	2.6
E_CW	Y	9 Tubes	263.8 ± 64.2	569.8	228	2.5
T_A	No need	12 panels	411.5 ± 103.2	888.9	432	2.1
T_N	Y	9 Tubes	186.7 ± 39.3	403.2	196	2.1
E_WW	Y	9 Tubes	210.8 ± 51.0	455.3	229	2.0
T_N	No need	12 panels	378.4 ± 95.4	809.6	428	1.9
T_M	Y	9 Tubes	168.0 ± 39.1	326.9	193	1.9
T_M	No need	12 panels	387.3 ± 99.4	836.5	442	1.9
T_Y	Y	9 Tubes	168.3 ± 34.7	363.5	188	1.9
S_R	No need	12 panels	291.0 ± 71.3	628.6	334	1.9
T5FL_CW	Y	9 Tubes	250.0 ± 57.5	540	283	1.9

[a] *Measured at a distance of 10 cm under light except the T5FL treatment (at 20 cm).*
[b] *Area of culture bed on bench layer = 1.8 m × 1.2 m = 2.16 m^2.*

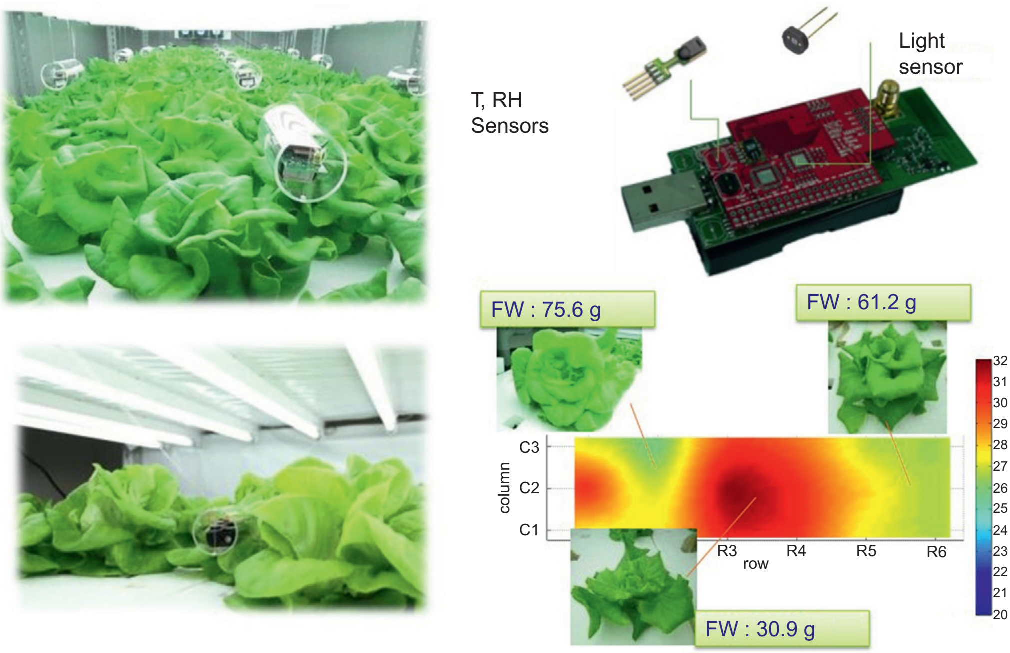


FIGURE 3.10

Wireless sensing nodes in PFAL.

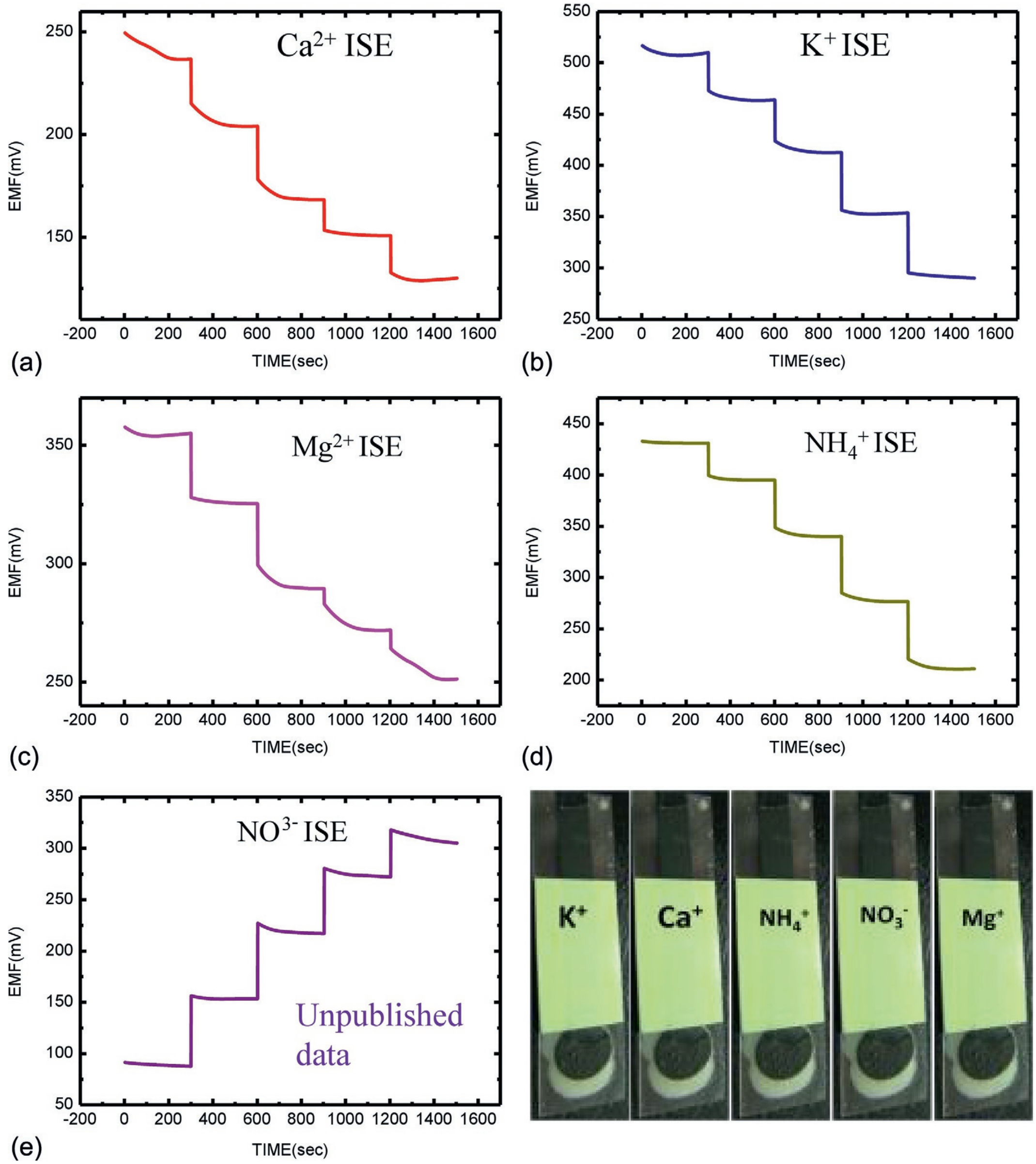


FIGURE 3.11

Sensing responses of screen-printed ion-selective electrodes (ISEs) for Ca^{2+}, K^{+}, Mg^{2+}, NH^{4+}, and NO^{3-}.

can also be used to measure plant growth as an independent system. Figure 3.12 shows a schematic diagram of the plant growth measurement system. For the weighing system, the load cell signals are calibrated, acquired and displayed in real time. The data are analyzed in correspondence with the plant geometric features obtained from the imaging system, enabling a plant growth model to be developed for various controlled environmental conditions. This plant growth measurement system provides a nondestructive, real-time processing approach over the traditional measuring methods. Furthermore, because it is automated, the system can gather a large number of plant measurements easily. Hence, the system is an efficient, practical tool for optimizing the parameters of the growing environment and plant factory environment.

BUSINESS MODELS OF PFALs IN TAIWAN

PFALs are eye-catching and new to the general public, and are attractive to consumers who are concerned about the environment and health. However, without a proper business model and careful planning, a PFAL business may fail. There are various business models being tested in Taiwan.

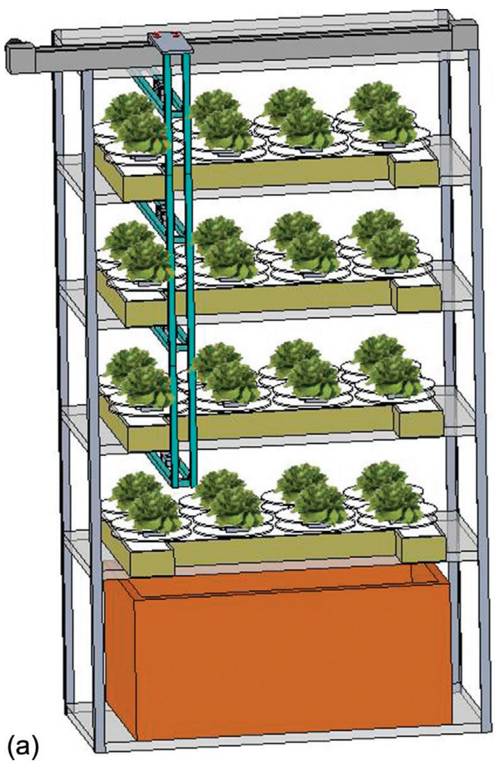
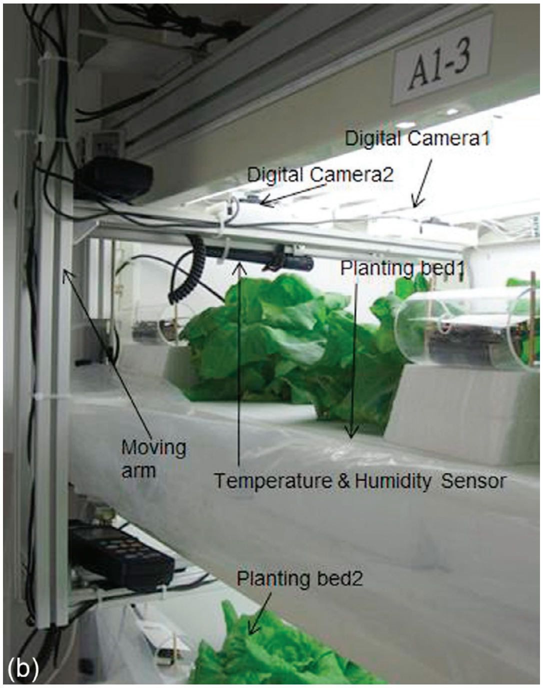


FIGURE 3.12

The nondestructive plant growth measurement system. (a) Schematic diagram of the system,

(Continued)



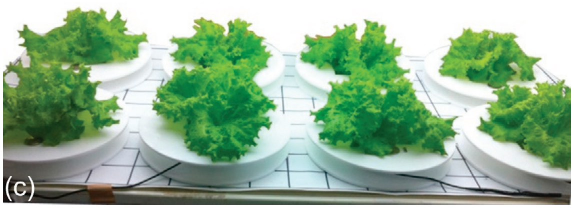


FIGURE 3.12—CONT'D

(b) the imaging system integrated with temperature and humidity sensors, (c) the plant weight measurement devices.

The product can be the plant itself such as whole plant, loose leaf, or baby leaf. The way to present the product is very important, such as using a sealed soft plastic bag, a soft plastic bag with tiny holes, or a sealed hard plastic box for the packaging. Different packaging methods express different concepts to the customer. Is it a product that does not need to be washed before eating, or like products grown in a greenhouse? It is important to emphasize that the product is locally made, not imported. Some products are provided with salad dressing, so the taste of the dressing is also important. One common matter is that the packaging bags and boxes be well designed to give a better appearance than traditional agricultural products.

The sales channels can be membership based, through a web site, within the company, or within the local community. It is important to limit the amount sold through third parties. The products can be sold through supermarket chains (owned by others) only temporarily, since the shelf charge is normally too high. Thus, for PFAL products, B2C (business to consumer) is much more favorable than B2B (business to business). C2B is even better and will be the direction to go.

If the company cannot sell all its products, other product lines may be considered. One company in Taiwan has developed more than 10 kinds of processed products such as ice cream, egg roll, bread, noodle, face mask, and skincare soap. The products can also be used as a nutritional additive in various forms such as juice, powder, and tablet. Different kinds of vegetable additives have different prices for the same product. For example, noodles with butter-lettuce and with ice-plant differ in price.

One construction company combined the PFAL concept in its community construction plan. Each family will have a home appliance style device for growing vegetables at home, and the community will have a service division that provides seeds, seedlings, stock nutrient solutions, and other needed supplies to community residents, thus promoting a green lifestyle.

Shops with a PFAL in the back or to one side, and with a restaurant or stand selling organic products in front, are a popular business model in Taiwan. Such shops are normally chain stores and are located throughout a city.

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

Some companies are capable of constructing PFALs for others, and most of them have a demonstration site that potential customers can visit for further consideration. Some successful companies will have a demonstration site with a more convincing scale, with a daily production of no less than 100 plants, and need to be operated smoothly for more than several months. An established marketing channel is a great advantage. Unfortunately, few companies meet these requirements, and so are less convincing.

Many PFAL-related hardware providers such as LED providers, clean room constructors, air conditioning system providers, hydroponics system providers, power supply providers, and thermal insulation providers have started to build PFAL demonstration rooms and are learning how to grow plants. Their common goal is to become a turnkey provider of PFALs.

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

1. The PFAL produces leafy greens for their own usage. For example, restaurant owners and corporations with more than 1000 employees.
2. The PFAL produces leafy greens for internet customers and members. Some companies are quite flexible, and even exchange membership with other health-related organizations such as yoga clubs.
3. The PFAL produces leafy greens and processed products as vegetable additives.
4. The PFAL produces leafy greens as an eye-catching sales point, but profit is made by other means such as the construction of chain stores selling organic dry foods.
5. Home appliance style PFAL module providers with a demonstration room.
6. Home appliance style PFAL module providers having alliances with the construction industry.
7. PFAL related hardware providers which build PFAL demonstration rooms to sell their products and which plan to become turnkey providers.
8. PFAL turnkey builders and consultants with or without a PFAL demonstration room.

As described above, PFAL companies in Taiwan are still small in scale but are flexible and willing to try various business models. Some look promising, some have failed. Even with the same business model, some companies succeed while others fail, as in any emerging industry.

CONCLUSIONS

The PFAL business is booming in Taiwan. The number of booths attending the PFAL Expo has tripled in 3 years. Without financial and policy support from the government, private companies are entering this new industry with great zeal. PFAL-related NPO organizations have been established, enabling the horizontal and vertical connection and integration of companies.

At present, there is no private agricultural organization involved in the PFAL business in Taiwan. Several farmers' associations have considered converting unused warehouses to PFALs, but finally abandoned the idea. The high initial cost is the first concern, followed by the difficulty of finding skilled workers and managers to run the PFAL. At present, there are not enough skilled, qualified managers and workers in the PFAL industry in Taiwan. Besides academic training in undergraduate and graduate schools of Taiwan, our team also runs 30-h workshops twice a year and has trained more than 400 people so far, but less than 10% of them have gone into the business afterward. To capture worldwide business opportunities, it is crucial to train skilled managers and workers for the PFAL industry.

Many companies have become involved with a view to the business opportunities of turnkey projects. However, some failed to prove that their system can grow quality plants efficiently. Unfortunately, some companies saw PFALs as a quick way to make money, resulting in law suits and public distrust. Of the 11 international turnkey PFALs built by Taiwanese companies so far, are all in China.

Some consumers question the use of artificial lights and hydroponics, and there were complaints about the non-natural use of chemicals 3 or 4 years ago. Public awareness, food safety problems, environmental problems, and frequent media reports about PFALs help consumers to learn about the technologies, appreciate them and be willing to pay extra to buy PFAL products. Nevertheless, it is necessary to reduce the cost, increase the value, and increase the varieties that can be grown in PFALs. PFALs will coexist with organic agriculture and traditional agriculture, and will also play a key role in urban agriculture in the smart cities of the future.

KOREA

Changhoo Chun

Department of Plant Science, Seoul National University, Seoul, South Korea

PFAL INDUSTRY, A COMMITMENT TO THE FUTURE

The convergence of information and communication technology (ICT) in the farming business has been considered to be one of the measures for mitigating climate change, heralding a paradigm shift in agricultural production, and creating new growth in Korea. In 2013, the Korean government announced its "Plan for promotion of agri-food and ICT convergence" in order to apply ICT technologies to the production, distribution, and consumption of agricultural products. One of its major projects which is already being implemented is the supply of smart greenhouse systems that support the monitoring and control of plant cultivation environments via smart phones, by providing high-tech sensing, monitoring, and controlling equipment to farms. PFAL, the most advanced type of farming system, has gained general acceptance as a highly successful application of ICT-converged smart farming systems.

In 2009, the Ministry of Knowledge Economy (MKE) started a research project named "Development of major components for IT-LED based plant factories." Several national policy support projects such as "Construction of business ecosystems based on plant factories" (2012, MKE) and "Demonstration support project for promoting the plant factory business" (2013, Ministry of Agriculture, Food and Rural Affairs) were also implemented along with some support projects funded by local governments. These policy support projects have been created because PFALs are recognized as a promising export to foreign countries even though this high-tech equipment industry was seldom economically feasible in the domestic market at the time.

RESEARCH AND TECHNICAL DEVELOPMENT

Korea has developed various technologies for vegetable breeding, hydroponics, greenhouse structure, as well as hardware and software for environmental control in greenhouses, which can easily be diverted to vegetable production in PFALs. Even though many element technologies for PFALs have been developed and related research results have been published, no commercialized PFAL was introduced until 2009, whereas vegetable production in greenhouses has become crucial to Korea's agriculture sector. Universities and national and prefectural research agencies were the main agents for research and technical development (RTD) in the area of controlled environment agriculture (CEA) that enables the grower to manipulate the cultivation environment to the desired conditions and that is useful for isolating specific environmental variables for more precise studies on plant responses to modified sets of environment. There is obvious commonality in research areas between PFAL and CEA with artificial lighting.

Prior to 2009, most practical research studies on PFAL (or CPPS) were performed using fluorescent lamps as the artificial light source. Some representative samples of related RTD in those days were CPPS for producing plug transplants of seed-propagated vegetables for the nursery industry; CPPS for producing vegetatively propagated strawberry transplants for consolidating the national proliferation program; CPPS for producing a monocotyledonous vegetable as a raw material for an instant ramen company; and CPPS for producing a salad vegetable for a restaurant chain, a fast-food chain, and a vegetable processing and distribution company. Total solutions were developed for each system and delivered to contracted enterprises, which included the cropping system, cultivar selection, seed sterilization, seed germination, raising transplants, transplanting, planting density, temperature settings for air and nutrient solution, setting of photo and dark periods, PPF setting, harvest scheduling, and so on.

The biggest change in RTD between the time before and after the year 2009 was the use of LEDs as the sole light source of PFALs. Of course, the physiological and morphological responses of plants grown under red, blue, green, or even far-red monochromic light sources and under combinations of those monochromic sources were studied scientifically from the late 1990s. Due to the low luminance and high cost of LEDs, however, they were not widely used as a light source for PFALs until 2009 in Korea.

Research and development of PFALs with LEDs dramatically increased from 2009. The trigger was the adoption of a "Low-carbon, green growth campaign" as a national policy and "Development of major components for IT-LED based plant factories" was selected as one of the smart projects in that year. Four other major research projects funded by the government relating to PFALs with LED lighting were: "Development of LED-IT based plant production techniques for environment-friendly horticultural products," "Development of lighting techniques using LEDs that have a particular spectra promoting plant growth," "Commercialization for exports of plant factories," and "Development of urban-type PFAL technology."

As various types of LED chips with different wavelengths and wattages and LED lighting fixtures with different shapes, combinations of spectra, and luminance have become available in the market, research on PFALs with LEDs has sharply increased not only at universities and public research agencies but also private companies. A large number of research results on the photosynthesis, growth, and morphology of various vegetables in response to different PPF ratios of blue and red LEDs have been published in international and domestic journals including *Horticulture, Environment, and Biotechnology*, the *Korean Journal of Horticultural Science & Technology*, and *Protected Horticulture and Plant Factory*. And as the PFAL business has expanded, private companies have started accumulating their own confidential research data on lighting equipment such as white LEDs having different spectra, productivity, cropping systems, cultivation methods, specialized quality, and even profitability.

PFALs for research by national research agencies have been installed at the Antarctic King Sejong Station (55 m^2) of the Korea Institute of Ocean Science; the National Academy of Agricultural Science (446 m^2 in Suwon-si, and 1506 m^2 in Wanju-gun) of the Rural Development Administration (RDA); Protected Horticulture Research Station (142 m^2 in Haman-gun) of RDA; National Institute of Horticultural and Herbal Science (55 m^2 in Umseong-gun) of RDA; and Korea Institute of Science and Technology (33 m^2 in Gangneung-si). Meanwhile, PFALs of prefectural research agencies have been installed in the Agricultural Research & Extension Services of Gyeonggi-do (115 m^2 in Whaseong-si); Chungcheongbuk-do (413 m^2 in Cheongju-si); Gyeongsangbuk-do (132 m^2 in Daegu-si); and Gyeongsangnam-do (198 m^2 in Jinju-si). PFALs for research by universities have been installed at Seoul National University in Seoul-si and Suwon-si; Chungbuk National University in Cheongju-si; Gongju National University in Yesan-gun; Gyengsang National University in Jinju-si; and Jeonbuk National University in Jeonju-si and Iksan-si.

PRIVATE COMPANIES AND FARMS IN THE PFAL BUSINESS

As mentioned above, several private companies have entered the PFAL business since 2009 and currently about 30 companies are operating PFALs for demonstration and/or production. They have also installed PFALs for their customers in Korea and other countries including Japan, China, Mongolia, and Qatar, the customers being local cities and boroughs, agricultural research centers of local government bodies, universities and schools, cafes and restaurants, hospitals, mega marts and department stores, community centers in apartments, farms, and others.

Most of the companies which have installed PFALs for research, demonstration, and/or production and are currently operating them can mainly be classified as small and medium-sized enterprises. These include Paru (20 m^2 in Suncheon-si), Insung Tec (165 m^2 in Yongin-si), Taeyoun Eco & Agro-Industry (165 m^2 in Seoul-si), KAST Agricultural System & Technology (132 m^2 in Gumi-si), Korea Refrigerated Foods (50 m^2 in Gimhae-si), Yuyang DNU (9 m^2 in Hwanseong-si), Cham Farm (50 m^2 in Goseong-gun), Jinwon Farm (330 m^2 in Gwangju-si), Wise Control (33 m^2 in Yongin-si), Refresh Hamyang (1694 m^2 in Hamyang-gun), Vegetechs (661 m^2 in Goyang-si), Future Green (50 m^2 in Suwon-si), Miraewon Farm (604 m^2 in Pyeongtaek-si), Happy Enjoy Farm (200 m^2 in Gyeongsan-si), Maxfor (115 m^2 in Yongin-si), and Eum Farm (226 m^2 in Gimpo-si). Some of the companies classified as large-scale enterprises such as Dongbu Lightec (9 m^2 in Bucheon-si), Nongshim Engineering (230 m^2 in Anyang-si), Lotte Mart (9 m^2 in Seoul-si), and Lotte R&D Center (17 m^2 in Seoul-si) are operating PFALs mainly for research.

ACHIEVEMENTS AND CHALLENGES

The PFAL and related industries in Korea have grown dramatically in just 5 years. A recent report from RDA (Lee, 2014) estimated that the market size of the domestic PFAL business is about US$577 million per year; with US$77 and 500 million as added values from the PFAL itself and industries with forward/backward linkages, respectively.

All the element technologies for PFALs have been successfully developed from a series of systematically designed joint researches among multidisciplinary experts. In practice, the lighting technology for PFALs in Korea skipped the stage of fluorescent lamps and LED technology was directly applied, causing serious problems such as high initial investment and difficulties in cultivation due to lack of information. Nevertheless, the Korean PFAL industry has had a great opportunity to confidently compete against other PFAL-advanced countries (Chun, 2014).

Policy support projects prepared by the government were also efficient for the early stage of development of PFALs in Korea. Further investment from the private and public sectors is needed to achieve stable growth of this industry in terms of networking of minor PFALs for ensuring successful marketing of their products, and the development of high value-added products by meeting the various demands of today's aging, health-aware society. Unlike in Japan, PFALs in Korea are not subsidized by national or provincial governments. The PFAL industry would develop further if a subsidy program were to be introduced as PFAL-related technologies approach successful deployment on a commercial scale.

CHINA

Qichang Yang

Institute of Environment and Sustainable Development in Agriculture, Chinese Academy of Agricultural Sciences, Beijing, China

Yuxin Tong

Institute of Environment and Sustainable Development in Agriculture, Chinese Academy of Agricultural Sciences, Beijing, China

Ruifeng Cheng

Institute of Environment and Sustainable Development in Agriculture, Chinese Academy of Agricultural Sciences, Beijing, China

DEVELOPMENT OF PFAL IN CHINA

In China, studies on PFAL technologies began in 2002 and mainly focused on hydroponic technologies and their control systems, supported by the Ministry of Science and Technology of China. Since then, R&D on PFAL in China has advanced rapidly. By 2013, about 35 plant factories had been built, as shown in Figure 3.13 (Table 3.3), distributed in nine cities or provinces, including Beijing, Shandong, Shanghai, Nanjing, Changchun, and Guangdong. The PFALs in China are mostly located in research institutes and parks and are used for research and demonstration.

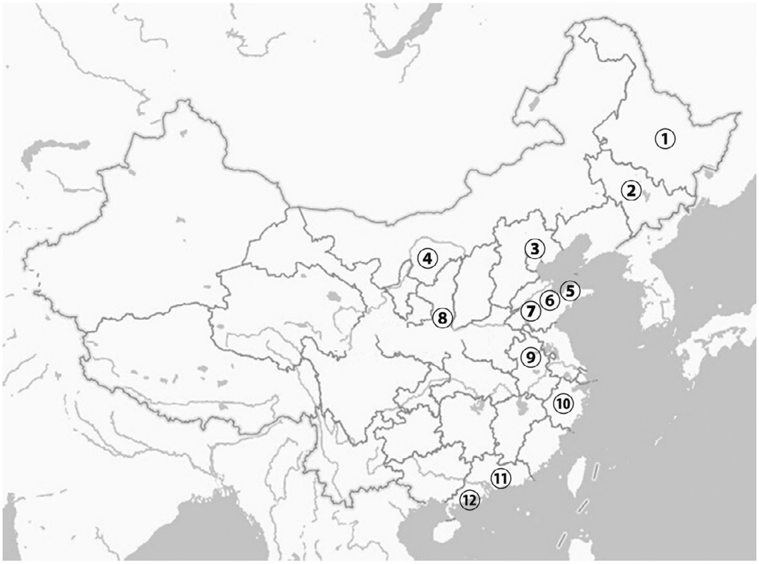


FIGURE 3.13

Regional distribution of PFALs in China (2013).

Table 3.3 Supplementary Table of Figure 3.13

No.	City/Province	Floor Area (m^2)
1	Harbin, Heilongjiang	12
2	Jilin	200
3	Beijing	3069
4	Inner Mongolia	100
5	Shouguang, Shandong	200
6	Gaoqing, Shandong	616
7	Ningyang, Shandong	72.9
8	Xian, Shanxi	200
9	Nanjing, Jiangsu	300
10	Changxing, Zhejiang	800
11	Zhuhai, Guangdong	30
12	Jianjiang, Guangdong	12

CASE STUDY OF TYPICAL PFALs

PFALs in the Chinese Academy of Agricultural Sciences

Since 2002, researchers in the Institute of Environment and Sustainable Development in Agriculture (IESDA) at the Chinese Academy of Agricultural Sciences (CAAS) have been studying PFAL technologies. In 2005, a PFAL with fluorescent lamps, a PFAL half with LED lamps, and a PFAL with

FIGURE 3.14

PFAL labs built in CAAS in 2005 (Left: fluorescent lamps, 20 m^2); in 2009 (Middle: half with LED lamps, 100 m^2); and in 2013 (Right: LED lamps, 100 m^2).

all LED lamps were built in turn at CAAS (Figure 3.14). The research conducted at CAAS focused on energy-saving technologies, LED energy-saving technologies, nutrient solution management, and vegetable quality control technologies for PFALs.

In 2012, a PFAL with a floor area of 80 m^2 was built in a greenhouse complex in the demonstration center of CAAS, which has a total floor area of 40,000 m^2 (Figure 3.15). The demonstration center is operated by Beijing IESDA Protected Horticulture Co., Ltd., which manages more than 10 PFALs in China (Table 3.4). The demonstration center is divided into seven function halls for exhibiting new PFAL technologies, new cultivation methods, and new ideas on urban, household and/or office horticulture. Recently, a three-layer vertical farming model was built in the demonstration center, which has an underground layer for mushroom production, a middle layer for leaf vegetable production with artificial light, and a top layer for fruit vegetable production with sunlight.

PFAL of Beijing Kingpeng International Hi-Tech Corporation

In 2010, Beijing Kingpeng International Hi-Tech Corporation, belonging to the Beijing Agriculture Machinery Institute, built a PFAL with a total area of 1300 m^2 (Figure 3.16). The PFAL includes a tissue culture room, seedling room, artificial light culture room with solar light generation technologies, vegetable storage room, etc.

Plant factory of Zhejiang University

The plant factory of Zhejiang University was built in 2013 in Changxing Agricultural Station. The total area of the plant factory is 1600 m^2 (area of PFAL: 800 m^2), and it has 10 layers of movable cultivation beds to increase the efficiency of land use (Figure 3.17). Many research teams of Zhejiang University, including control science and engineering, light engineering, computer science and technology, agricultural engineering, biological engineering, and horticulture and plant nutrition, are working together to improve PFAL technologies.

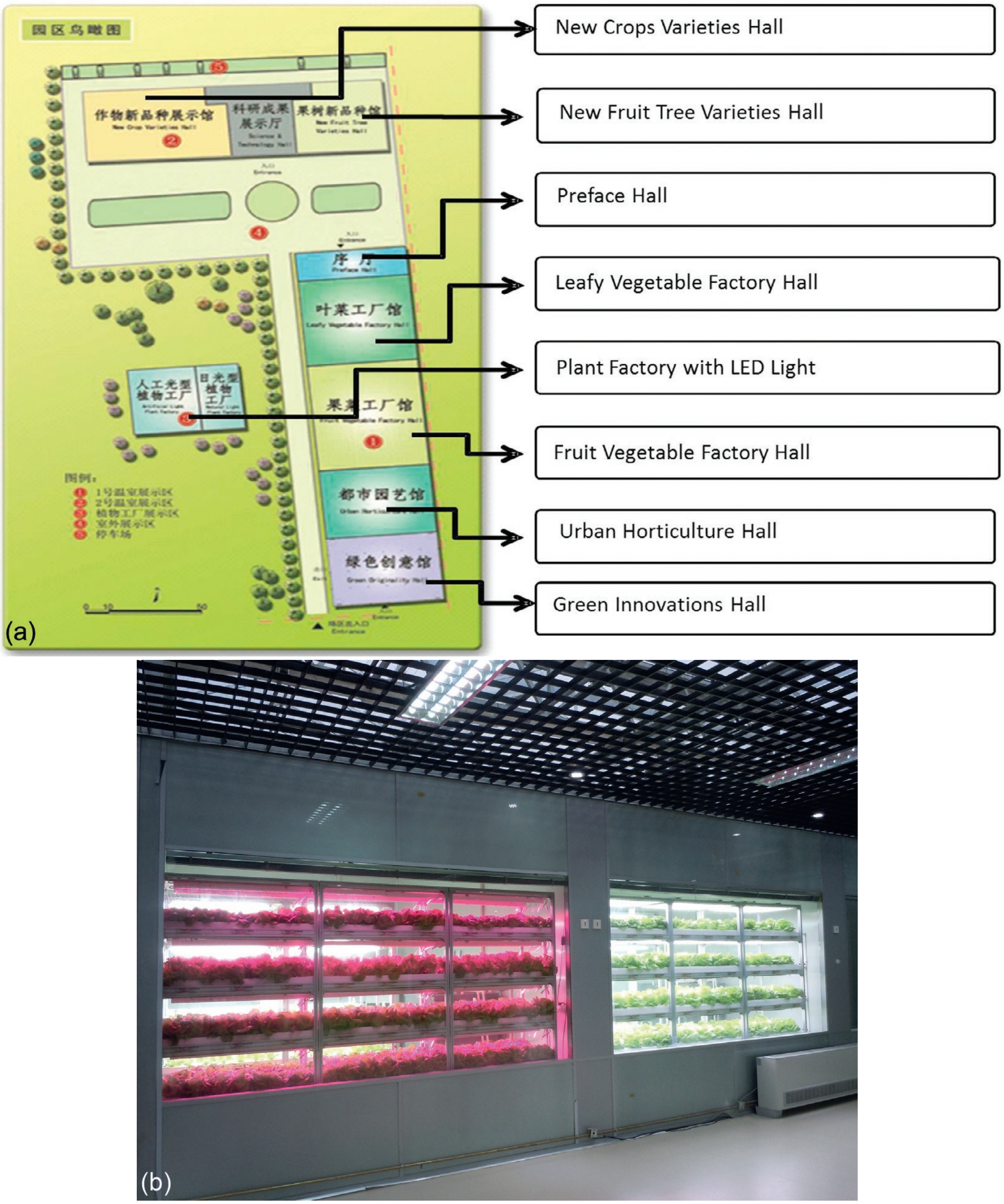


FIGURE 3.15

(a, b) Demonstration center of PFAL built in 2012 in CAAS.

Table 3.4 PFALs Built by Beijing IEDA Protected Horticulture Co., Ltd			
Name of PFAL	**Area (m^2)**	**Year**	**City or Province**
Changchun	200	2009	Jilin
Zhuhai	30	2010	Guangdong
Nanjing Tangshan Cuigu	300	2010	Jiangsu
National Agricultural Technology Demonstration Park	60	2011	Beijing
Kanjiangislets	12	2011	Guangdong
Ningyang	73	2012	Shandong
Qinlan	9	2012	Shanxi
Bayannur	73	2012	Inner Mongolia
Beijing	76	2012	Beijing
Haerbin	12	2012	Heilongjiang
Fengdong	40	2013	Shanxi

FIGURE 3.16

PFAL built by Beijing Kingpeng International Hi-Tech Corporation in 2010. Left: external appearance of the PFAL, 1300 m^2; Right: internal appearance of the PFAL.

FIGURE 3.17

PFAL built in Zhejiang University in 2013. Left: Bird's eye view of the PFAL, 1600 m^2; Middle and Right: Movable cultivation beds with LED lighting.

PFAL with LED in Shouguang

Shouguang city plays a very important role for developing protected horticulture in China, as it hosts the China International Vegetable Fair every May, attracting more than 2 million visitors. New technologies for protected horticulture are exhibited at the fair. In 2009, a PFAL with LEDs (40 m^2) was first exhibited at the 10th China International Vegetable Fair, and this new plant production system attracted the attention of millions of visitors. The area of the PFAL was enlarged to 200 m^2 at the 11th Fair in 2010. New technologies for LED energy saving, hydroponics, multicultivation of fruit vegetables and leaf vegetables, intelligent control systems, and so forth were demonstrated at the PFALs (Figure 3.18).

RESEARCH PROJECTS ON PLANT FACTORIES IN CHINA

In 2013, the National High Science & Technology Project on intelligent plant factory production technology (2013–2017; 46 million yuan (1US$ = 6.27 yuan)), organized by CAAS, was supported by the Ministry of Science and Technology of China. Fifteen universities, institutes, and companies joined the project (Table 3.5).

FIGURE 3.18

PFAL in Shouguang city. Left: PFAL with LED lighting, 200 m^2; Middle: multi-cultivation of fruit vegetables; Right: multi-cultivation of leaf vegetables.

Table 3.5 National High Science & Technology Project on Intelligent PFAL Production Technology

Item	Key Technologies	Participating Universities, Institutes or Companies
1	Energy-saving LED light source and intelligent light environment control	CAAS
		Institute of Semiconductors, Chinese Academy of Sciences
		Zhejiang University
		Beijing IEDA Protected Horticulture Co., Ltd.
2	Equipment of multilayer cultivation system	Beijing Agriculture Machinery Institute
		China Agriculture University
		Beijing Kingpeng International Hi-Tech Corporation
		Lhasa National Agricultural Science and Technology Demonstration Park
3	Energy-saving environmental control based on light and temperature coupling	Tech. Top Photoelectric Technology Company
		Nanjing Agricultural University
4	Nutrient solution management and vegetable quality control	CAAS
		Northwest A&F University
		China Agriculture University
		Beijing University of Aeronautics and Astronautics
5	Intelligent control system based on the network management	The National Engineering Research Center for Information Technology in Agriculture
		Vegetable Research Center of Beijing Academy of agriculture and Forestry
		China Agriculture University
		Jilin University
6	Integrated technology demonstration of solar light plant factory	Dushi Green Engineering Company
		Shanghai Jiao Tong University
		Tongji University
7	Integrated technology demonstration of PFAL	Zhejiang University
		IEDA, CAAS

NORTH AMERICA

Chieri Kubota

School of Plant Sciences, The University of Arizona, Tucson, Arizona, USA

HISTORY

The United States introduced PFAL for crop production in the 1980s. Those earlier facilities were producing leafy crops using deep flow technique (DFT) hydroponic systems under high-intensity discharge (HID) lamps inside a building. Among them, a commercial lettuce production facility located in Dekalb (west of Chicago) in Illinois operated for many years before their closure in the early 1990s. In the early 2000s, production of plant-made pharmaceuticals (AKA molecular farming) became a viable application of PFAL. In fact several large-scale commercial facilities were built in the US and Canada to produce pharmaceutical protein products (antigens and antibodies) using genetic modification or transient expression of plants. Then more recently, coinciding with the increasing interest of local food production, several large commercial PFAL facilities were built within close proximity to mega cities (such as Chicago). In addition, as a unique application, a small PFAL was developed to produce fresh vegetables in the US South Pole Station. This 22 m^2 footprint facility produced over 30 different types of crops (several at one time) including tomatoes, lettuces, and herbs for the crew year-round (Patterson et al., 2012). The facility also has an adjacent room (9 m^2) separated by a glass wall for research station personnel to experience the bright plant growing environment. This human psychological support by providing green plants was critical in such an isolated environment as the South Pole.

CONTRIBUTION OF SPACE SCIENCE

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

CURRENT STATUS AND FUTURE PROSPECTIVE

As of 2014, there were a small number of commercial PFALs for food production in North America. For transplant production, there is at least one company producing grafted tomato seedlings using PFAL. More PFALs could be reported as being operated if statistics included medicinal crop production (such as medicinal *Cannabis spp*. or plant-made pharmaceutical production). However, finding the actual number and production capacity is challenging as there are no statistics generated by reliable organizations. Typical crop species grown in North American PFALs include leaf lettuces, basil, and micro/baby greens. Baby greens and microgreens definitions are often vague, but generally microgreens are at the beginning of first true leaf expansion and baby greens include a few true leaves. Because of the limited shelf life of these small greens, PFALs are well suited for such applications. Typically many different leafy crops are produced in the same growing facility. Some facilities are certified organic producers and/or implement aquaponics.

Regarding facilities, many of these utilize a multitiered production system with LED, induction or fluorescent lamps installed in each tier. The distance between tiers is relatively large (~1 m) compared with what is commonly seen in Japan and other Asian countries, presumably primarily considering logistics and accessibility to the plants instead of space use or energy use efficiency. CO_2 enrichment is not a common practice as the production systems are often located inside the voluminous space of warehouse buildings. Such buildings often have air handling systems with minimum ventilation to assure human health and the growing space is often shared with CO_2 emitting workers who are engaged in activities such as transplanting, harvesting, and mixing nutrient solution. As a result the CO_2 concentration inside the growing facility is, anecdotally, not at problematic low levels such as we may experience in a truly contained environment. Use of automation is limited. Logistical improvement of workers moving plants from seed to harvest may be a critical area for future R&D.

It is hard to generalize the business model of North American PFALs. However, one prominent trend among the commercial PFALs in North America may be the strong support from high-end retailers (grocery stores) that promote local food production and organic produce. Another trend is collaborations with resort hotels and restaurants. For example, there seem to be a few projects planned to build PFALs in the Las Vegas area to provide the fresh produce consumed by visitors and tourists. Given that the traditional supply chain in North America is driven by a small number of large-scale produce industries with a limited number of production regions (open field) selected based on the production scale and costs (mainly in California), local production of fresh produce is expected to continuously attract American consumers. For example, California (spring to fall) and Arizona (winter) together supply more than 90% of lettuces and other leafy crops consumed in US and Canada. PFAL will not replace this traditional open-field production currently going in California/Arizona but could be a sustainable alternative of specialty crops in the future. It is also critical to have academic research capacity to support this emerging industry sector. Forming industry associations may help but may not work as it does in Asian countries due to the competitive nature of venture capital in North America. The potential immediate role of academia may be providing opportunities for information exchange as well as needed education and training for those PFAL practitioners and planners. Increasing the number of online course opportunities in the area of controlled environment agriculture may help meet such needs.

EUROPE (ENGLAND, THE NETHERLANDS, AND OTHERS)

Chungui Lu

Head of Centre for Urban Agriculture, Centre for Urban Agriculture, University of Nottingham, Leicestershire, United Kingdom

BACKGROUND

Urban agriculture refers to agricultural practices in urban areas and their surrounding regions (peri-urban), and is a centralized operation involving horticulture, animal husbandry, aquaculture, and other practices for producing fresh food or other agricultural products. There are many different approaches to urban agriculture, including ground-level farming, rooftop farming, hydroponics, greenhouses and other new technologies. Urban agriculture has the potential to produce food for local consumption, especially perishables and high-value horticultural crops. Also, there is increasing interest in commercial-scale cultivation of nonfood crops in urban areas, such as flowers, green walls, and the like. Urban agriculture plays a key role in food security and is found in smart cities, which are a phenomenon closely related to urban economies, culture, science, and technology; urban agriculture indicates that a city's economic development has reached a higher level. Compared with other agricultural practices, urban agriculture makes intensive use of capital, facilities, technology, and labor. It is also an industrialized, market-oriented agriculture, and can take advantage of the developed markets, information and transportation networks of international cities to boost agricultural production and interregional trade.

Greenhouses were introduced several decades ago to protect plants from weather conditions. Initially they were used by farmers in farming areas as alternative ways to protect production. More recently, greenhouses including plant factories and roof gardens have been built in cities. An increasing number of companies and researchers have become involved in urban farming, successfully producing fresh food and other products in a sustainable way. Urban agriculture is being seen as an emerging business opportunity in urban areas.

PRESENT STATUS OF PLANT FACTORIES IN THE EU

Agriculture in the European Union faces some serious challenges in the 21st century that include: changes in climate, significant increase in urbanization, competition for water and vital resources, rising costs, decreasing growth in agricultural productivity, competition for international markets, and uncertainty about the effectiveness of current European policies (EGTOP/6/13). Plant factories (protected cultivation) have the potential to address some of the upcoming challenges.

The EU is one of the main global producers by glasshouse, particularly in countries such as the Netherlands, Spain and Italy. Global production in greenhouses is growing, currently with an estimated area of 800,000 ha, of which 20% (160,000 ha) is situated in Europe (EuroStat, 2011). This production system is characterized by the ability to change climatic conditions using various technologies and practices for greenhouse vegetable production.

Plant factory technologies have developed remarkably in the past decade in the EU, including computer-integrated systems for optimizing the growing conditions and efficiently using water, nutrients and energy (Morimoto et al., 1995; Vänninen et al., 2010). In a controlled environment, precise control over light quality, light intensity, photoperiod, humidity, carbon dioxide concentration, nutrient solution, pH, and temperature can all be achieved (Stutte, 2006; Kozai, 2013) to improve productivity and quality. In terms of lighting applications, new LED technology has made it possible to build plant factories.

Philips' Horticulture LED Solutions Group in the Netherlands has been developing LED lighting solutions for horticultural applications for more than 7 years, has proven the commercial feasibility of LED lighting for horticulture, and has recently started working on plant factories with artificial lighting (PFAL). Working in farming, which is defined as multilevel horticulture in a controlled environment, with an open innovation structure with both academic and commercial partners, Philips has developed commercial-scale solutions for city farming that are currently in operation and is working on several more. Examples include Green Sense Farms in the USA, Osaka University in Japan, and National Urban Park in the CAAS in China. The company also has a high-tech research facility at Stockbridge

Technology Centre in the UK, which conducts trials on the optimum light recipes to save energy and make production more profitable for future upscaling.

PlantLab, a privately owned Dutch company that specializes in controlled environment agriculture, was founded in the Netherlands in 2010. PlantLab's new international research center was officially opened by King Willem-Alexander on 30th September 2014 (Figure 3.19a). The company built its first commercial plant production units (PPU) in March 2010, and is currently investing over $22 million in a 200,000 square-foot headquarters and research facility, which will allow optimization of crop production and further improvements in its technology and expertise. PlantLab developed a patented technology to grow crops in plant production units, which are completely closed climate chambers without daylight. The opening of the new facility marks the start of a large-scale roll-out of the PlantLab

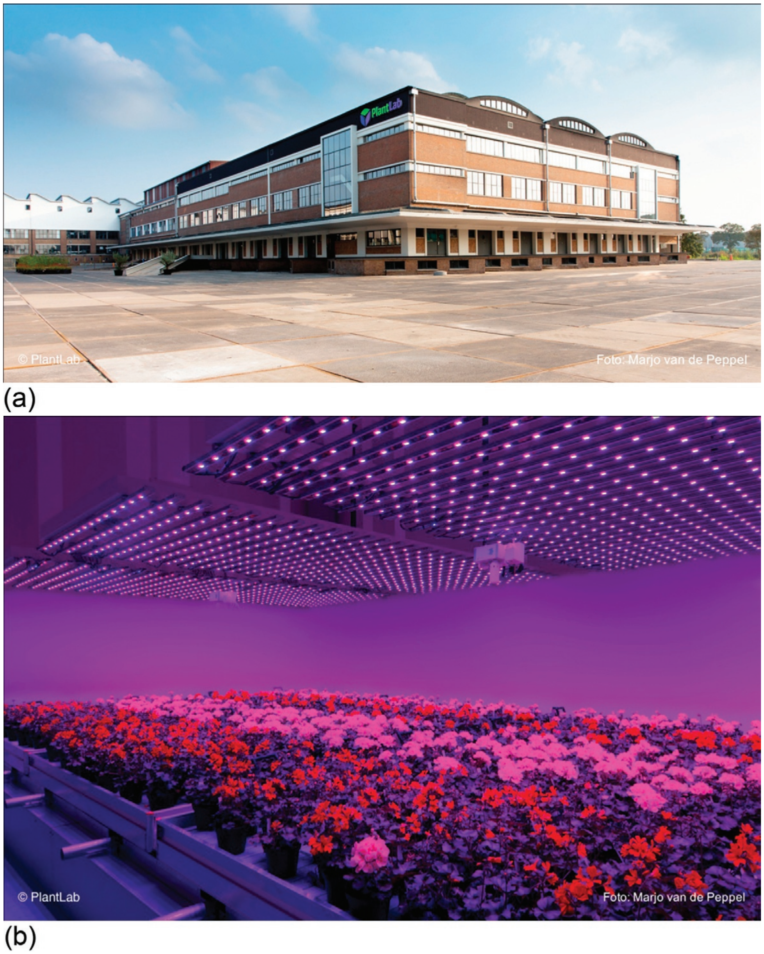


FIGURE 3.19

PlantLab new headquarters and R&D center (a) and plants growing under LED light (b).

concept with international partners in various industries. PlantLab launched an important first partnership with the Swiss breeding company Syngenta last year. PlantLab's method can be applied in many industries, ranging from the processing and production of vegetables, fruit and flowers, to the production of ingredients for children's food, medicines, flavors, fragrances and cosmetics.

By utilizing the advanced technology of PPUs and proprietary mathematical models, which have been developed over the past 25 years by the founders of PlantLab, as well as state-of-the-art LED systems (Figure 3.19b), air control technologies and optimum water control solutions, PlantLab's innovations remove the typical variables that hinder crop growth and delivery. This means it is now possible to accurately control crop yields, growing times, nutritional content, and other factors such as taste and appearance. In 2015 PlantLab will build a Dutch-based PPU for the production of fresh herbs and lettuces as a showcase for urban farming.

The Netherlands is the most advanced country regarding plant factories and protected glasshouse cultivation in the EU. In other parts of Europe, some small-scale vertical farms have been built, while construction has begun on some large-scale ones. In 2012, the Swiss company UrbanFarmers, a spin-off of the Zurich University of Applied Sciences (ZHAW), built a 260 m^2 greenhouse farm on an industrial rooftop in Basel (Graber et al., 2014). Together with the research team at ZHAW, this aquaponic farm was planned and built, and is now operated and monitored. In Sweden, Plantagon's Greenhouse, which will be a 17-story vertical farm that integrates sustainable growing systems, energy solutions and recycling, is approaching the start of construction (HortiDaily, 2014). Meanwhile, rooftop greenhouses (RTG) with an area of 250 m^2 are being built on rooftops for food production in Barcelona, Spain. Two small-scale land-based cyprinid fish farms that divert recirculating water into a closed-loop system with hydroponic beds have been developed in Slovenia. Such closed-loop systems could contribute to urban food production and higher sustainability by reducing the usage of water and chemicals while minimizing nutrient losses.

OUTLOOK FOR PLANT FACTORIES IN THE UK

Alongside the many challenges, the UK is becoming a world leader in agricultural technology, innovation and sustainability. The vision of the government's new UK strategy for agricultural technologies (www.gov.uk/government/publications/uk-agricultural-technologies-strategy) is to exploit opportunities to develop and adopt new and existing technologies, products and services to increase productivity, and thereby contribute to global food security and international development. To achieve this, the government is investing £70 m in a new Agri-Tech Catalyst. The government will invest £90 million over 5 years to establish a small number of Centers for Agricultural Innovation to support advances in sustainable intensification.

The University of Nottingham (UoN) is a leading academic institution in the agrifood industry; its School of Biosciences is the largest group of plant and crop scientists in any UK university. In order to improve food security, a Center for Urban Agriculture (CUA) has been established. Interestingly, a multidisciplinary group of staff from biosciences, engineering, environmental technology, and economics has been formed, with great potential to deliver research results; the group led by Dr. Chungui Lu has successfully organized two international conferences on urban agriculture and vertical farming. Two research projects on smart LED lighting systems (£1.5 m) and smart glasshouse LEDs (£0.5 m) at UoN have recently received funding under the Innovation UK Agri-Tech Strategy. Four PhD research projects in this area funded by EPSRC and CFFRC have begun. Through the projects, CUA has established a strong multidisciplinary team on sustainable agriculture. The Smart LED Lighting System uses sensors in precision farming to optimize horticultural crop yield, quality, and resource use efficiency in real time, providing light energy tailored to the demands of the plants. The Smart Glasshouse project provides a sustainable solution to the inherent problems of the greenhouse industry by the introduction of a low-cost energy saving and climate control system. Innovative technologies including effective heat-insulating solar glass, vacuum insulation panels, windcatchers, and LED lights will be used to reduce the heating and cooling load of commercial greenhouses, thereby reducing carbon emissions and improving the cost effectiveness of greenhouse production.

CambridgeHOK is a leading designer and constructor of glasshouses and control systems for academic and commercial growers with an annual turnover of £8–12 m. The company is already providing turnkey conventional glasshouse projects around the world, working at the forefront of production technologies. Its recent projects include those for the University of Nottingham, Stockbridge, and Cornerway's Nursery. In 2012 CambridgeHOK won the BCIA award for a control system at The Eden Project.

Stockbridge Technology Centre has built a new multitier LED4CROPS facility with LED lighting for studying the production of a wide range of crops from all sectors of the horticulture industry including ornamentals. The energy and cost price model varies widely according to each situation, so it is important to identify key "first to market" products and countries.

Paignton Zoo is currently experimenting with a high-density vertical growing system with a VertiCrop technology. VertiCrop is an experimental vertical irrigation system (Figure 3.20) designed to grow food for the animals of the zoo. In the summer of 2009, 11,900 plants were simultaneously grown on a set of rotating structures with 8 levels, 3 m high, covering a total ground area of 70 m^2. The system gives five times the yield of a typical field (Bayley and Yu, 2010), and can still be used during the winter months, demonstrating the adaptability of the system with minimal energy inputs.

In the UK, plant factories are still at the developing stage, and hence the scientific community is highly involved. While many small city farms already exist and are being developed, we believe that a truly commercial-scale alternative to conventional growing is yet to be developed. There are many

FIGURE 3.20

The VertiCrop growing production system in Paignton Zoo, UK.

companies in the UK developing products for plant factories. One such pioneer in the UK's hydroponics industry is HydroGarden, which is developing the latest technologies in hydroponic systems and LED lighting, and is moving products to market.

The development of plant factories not only involves "close to market" urban farm solutions but also creates networks of researchers to discuss current ideas, technologies, potential businesses and research. Recently, an International Vertical Farming and Urban Agriculture Conference (VFUA) was held in September 2014 in Nottingham, UK (http://VFUA.org). The conference successfully evaluated the benefits, opportunities, risks and challenges of urban farming and provided a forum for establishing research collaboration and networking among academic researchers and companies. The conference kicked off with Dickson Despommier, who is a pioneer of the VF movement. Jack Ng from Skygreens talked about his commercial vertical farm, which was the world's first. Other keynote speakers from China (Qichang Yang), Japan (Toyoki Kozai) and South Korea (Jung-Eek Son) presented their excellent works on urban agriculture and plant factories. Many companies from the UK, EU, USA, and other countries, including HydroGarden, Phillips, Illumates, PlantLab, and The FarmHere, showcased their products for plant factories and the new technologies they have used.

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