Status of Plant Factory Industry and Recent Research in Taiwan

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1. Abstract

Plant factory (PF) industry is booming in Taiwan. Especially the PF using only artificial light as the sole light source (PFAL in short) in multi-layer shelf with carbon dioxide enriched, in an air-tight and thermally insulated chamber/room. It catches global attention started in East Asia and now worldwide. This paper focuses on the introduction of current status of the industry in Taiwan and briefly introduces some research conducted in the Dept. of Bio-Industrial Mechatronics Engineering, National Taiwan University.

Keywords: plant factory, Taiwan, industrialization, research, PFAL

2. STATUS OF PFAL IN TAIWAN

It was estimated that 70% of the population will live in the city compare with the current 50% (Kozai, 2014). This forecast simply means that urban agriculture will play more and more important role in supply of bio-mass. As mentioned by Glaeser (2011), for the sustainability of the Earth, the development of the city should go up instead of going out. It is the same for the development of urban agriculture –vertical farming, especially PFAL is the answer. Many people in Taiwan share the same thought. We do believe that PFAL can make us richer, smarter, greener, healthier and happier.

There are 45 organizations engaged in leafy green production using PFAL in Taiwan as of Sept. 2014. Totally 56 small to large PFs were built and operated. Among these 45 organizations, there are two research institutes, four Universities and 39 from private companies involved as shown in Fig. 1. The PFs built by Universities and research institutes were financially supported by inner funds and from the government and no support from the government to private companies.

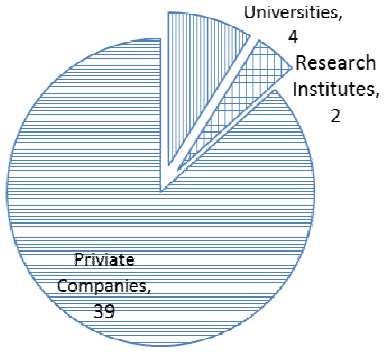

Fig.1 Distribution of PFAL in Taiwan categorized by organization before Sept., 2014

Among those 56 PFs, 73%, 20% and 7% are located in northern, central and southern Taiwan, respectively as shown in Fig. 2. The scale of PFs can be found in Fig. 3, they were categorized into six sizes based on amount of daily harvested assuming cropping density is 25 plants per square meter of cultural bed. In between the smallest (< 100 plants/day) and largest (> 10000) are 100 to 500, 500 to 1000, 1000 to 5000 and 5000 to 10000. Half of those PFs are small with daily production less than 100 plants and only one PF with daily production more than 10000 plants., they areprobablythe world largest PF with the daily harvest of 60000 plants (2.5 tons of leafy greens). Over 90% of PFAL are located in one room within a floor of an office building, some empty floor or basement inside a building in some industrial parks of Taipei area.

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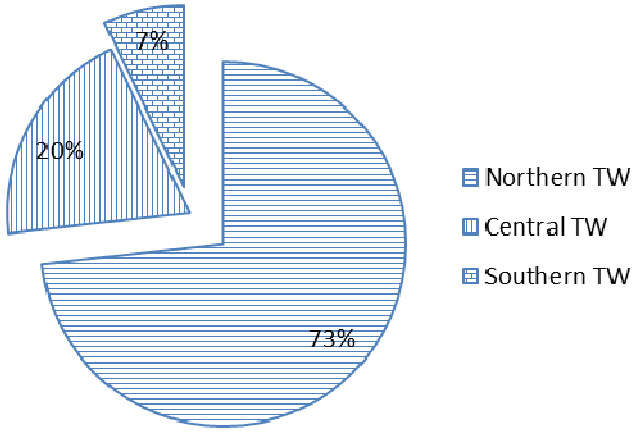

Fig.2 Geographical distribution of PFAL in Taiwan before Sept., 2014

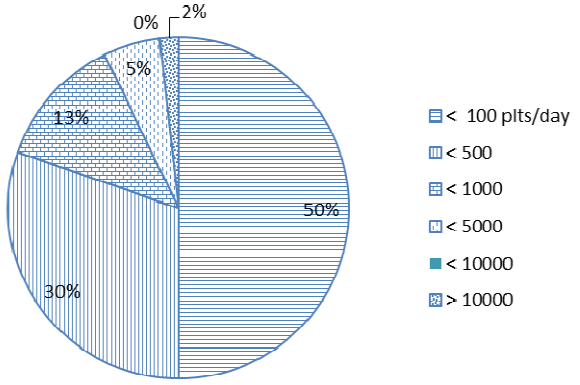

Fig.3 Number of PFAL in Taiwan categorized by daily production before Sept., 2014

Some companies started to export and built turn-key PFs abroad, mainly in China as shown in Fig. 4. Up to now, totally 11 projects took place and several has completed except two (in dashed line), one in Beijing and one in Xiamen. These two were suspended due to some financial reasons. Three out of 11 built the PFs in their own branch located in China.

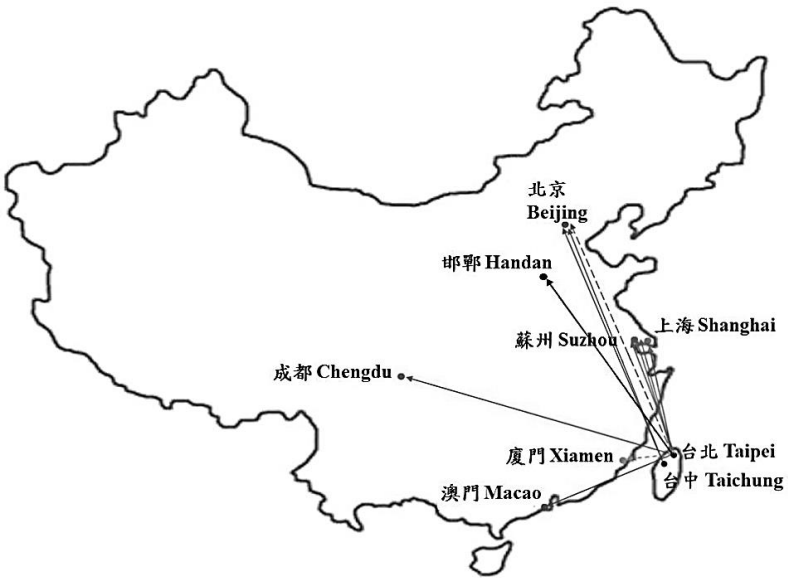

Fig.4 Export of turn-key PFALs from Taiwan to China

3. PFAL EXPO IN TAIWAN

To promote, exhibition and conference were held. PIDA (Photonics Industry & Technology Development Association) of Taiwan held photonics festival in Taipei, Taiwan for a consecutive of 23 years. PIDA is a NPO established by Taiwan Government to facilitate optoelectronic industry in Taiwan. Apart from an exhibition organizer, they also provide services such as industry research, consultation, promotion and communication in the industry and market. 2014 is the 3rd year they combine PF topic within the festival. Another two NPOs, Taiwan plant factory industrial development association (TPFIDA, founded in 2011) and Chung-hwa plant factory association (CPFA founded in 2012), were major co-organizers. The number of booths related to PFAL increased from 36 to 108 from 2012 to 2014.

Among the PF booths of 2014 expo, most of the companies demonstrate hardware used in PFAL. Several of them showed various spectrums and controls of LED tubes and panels. Some showed locally developed or imported nutrient control system. One booth was the Mirai-company from Japan showed the PF turn-key capability. Also several local companies expressed their capability in setting up PFAL abroad. At least five companies demonstrated the home appliance style plant growth desktop device and three showed growth bench to be used in the shop/restaurant/super market with or without controlled environmental capability. One company shows the LED illuminated green wall with the

air-cleaning capability. One company shows the aquaponics system. One company showed a variety of by-product with the PF grown vegetable ingredients.

4. PF Research

4.1 Costcomparison of PFAL

Crops grown in PFAL can be separated into 4 types: RTC, RTE (Ready To Cook, Eat)and CAW, EAW (Cook, Eat After Wash). The retail price of RTE lettuce and CAW Pak-Choi varied a lot, ranged from NT$500 to 2000 and NT$200 to 300 per kg, respectively. As shown in Table 1 are average retail price and cost of lettuce producedatJapan / Taiwan's PFALwithsame daily production of 1000 plants.

There are some fundamental reasons for this dramatic difference on production cost. Mainly, high construction cost and equipment, especially the LED cost, lead to high depreciation and high laborcost and electricity cost lead to high operating cost.

Table 1 Comparisons of retail price and cost of lettuce produced in Japan's & Taiwan's PFAL

Lettuce	Japan	Taiwan
Retail price*	¥150 ~ 200	¥81 ～ 420^
Cost*	¥80 ~ 100	¥47 ～ 56^

* in Japanese yen per 70 g fresh mass produced
^ exchange rate at 1 NT$ to 3 Japanese yen

4.2 Spectrums of LEDs used in PFAL

As shown in Fig. 5 is the spectrums of artificial light used in PFAL of Taiwan. Assuming the cultural bed is at the same size (1.8 m x 1.2 m), the comparison on light efficiency of various lights was listed in Table 2. The row with shadowed background showed that the LED-panels are less efficient in general when compare with LED-tubes with reflective film between tubes. Also, the longer the tube, the higher the overall efficiency in terms of quantitative measures using micro-mole per Joule as the unit.

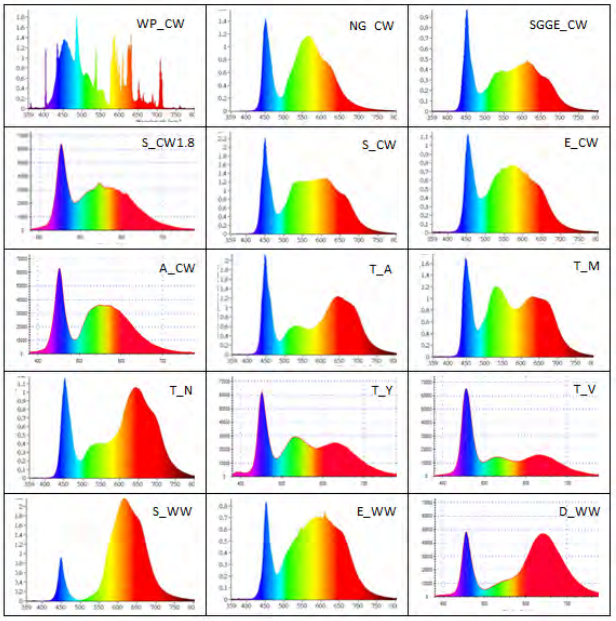

Fig.5. Spectrums of various artificial light used in PFAL (Fang, 2014).

Table 2 Comparison of efficiency of various lightsources used in PFAL (Fang, 2014)

Comp_Spec of Light sources	Reflectors on top	No. of tubes or panels	PPF* µmol m^{-2} s^{-1}	PPF x Area (µmol s^{-1})	Power consumption, W	Efficiency, µmol 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

*Measured at 10 cm distance under light except the T5FL treatment (at 20 cm distance)
**Area of culture Bed on bench layer = 1.8 m x 1.2 m = 2.16 m^2

4.3 WSN in PF

Wireless sensor network is used to evaluate the uniformity of air temperature,

humidity, and light intensity horizontally in a layer and vertically within layers of a PFAL (Cheng *et al*., 2011; Juo*et al*., 2012).Each wireless sensor module is equipped with temperature, relative humidity and light sensors, hanging on top of crops in each layer of cultural benches for the verification of the uniformity of distributions of light and air. As shown in Fig. 6, the temperature distribution is clearly related to the distribution of the fresh weight harvested. Means to increase the uniformity of temperature took place to reduce the variation on final fresh weight. A smart fan system was developed for such purpose (Lee *et al*., 2013).

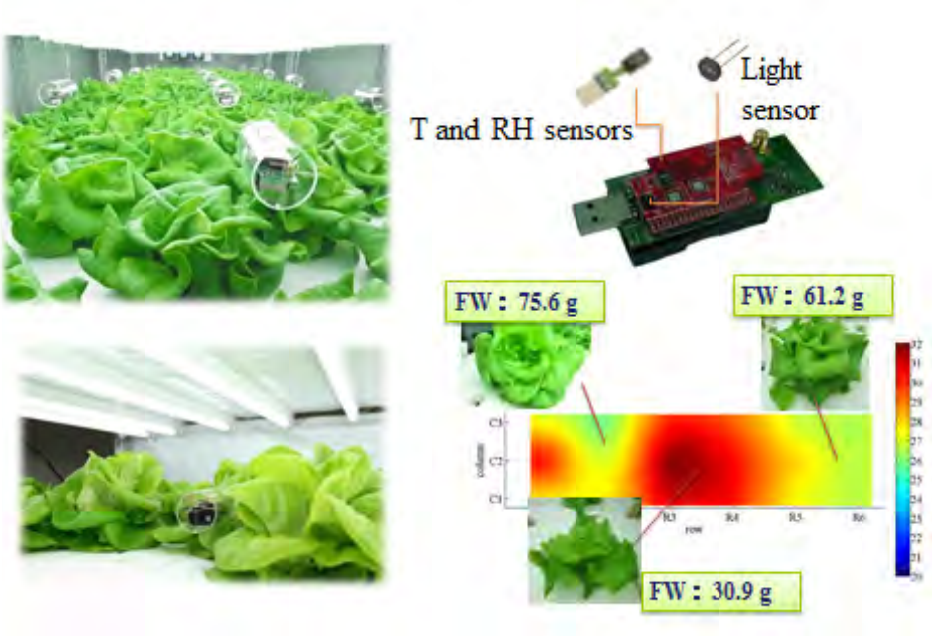

Fig.6. Wireless sensing nodes in PFAL

4.4 Ion-selective sensors for nutrient detection

Traditional ion-selective sensors were quite expensive and were short in usable lifespan. New ion-selective sensors for the detection of macro-elements in nutrient solution were developed. As shown in Fig. 7 are the sensing responses of screen-printed ion-selective electrodes (ISEs) for Ca^{2+}, K^{+}, Mg^{2+}, NH^{4+}, and NO^{3-}.

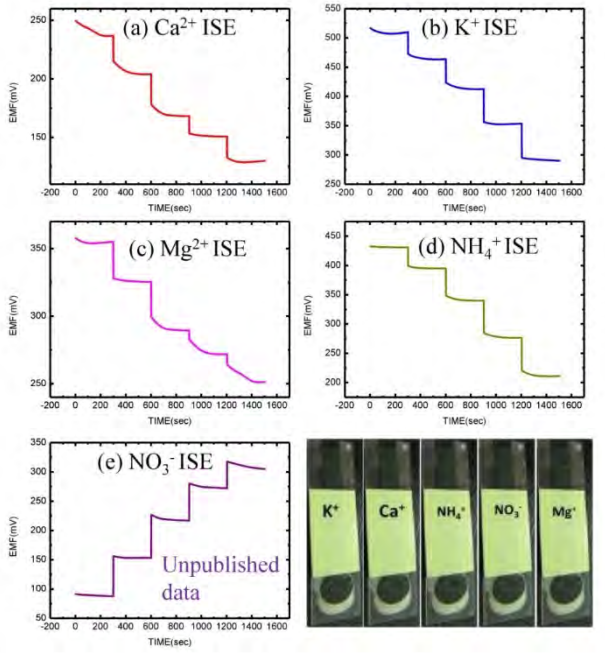

Fig. 7 Sensing responses of screen-printed ion-selective electrodes (ISEs) for Ca^{2+}, K^{+}, Mg^{2+}, NH_4^{+}, and NO_3^{-}.

4.5 Non-destructive plant growth measurement system

A measurement system with cameras attached to a sliding rail on each layer of cultural bench accompanyingwith weighing devices for each plant was developed for continuous and automatic plant growth measurement. The system is capable of taking images at preset time interval and stitches all imagesacross the cultural bed to form a panoramic image of the cultural bed using a computer with image processing capability.In the recordingprocess, the cameras moveacrossthewhole cultural bed in order to acquire images. Temperature and humidity sensors are also integrated with the imaging system to acquire spatial-temporal environmental information during the plant growth period. The image processing algorithms, that calculated geometric featuressuch as the projected leaf area, plant height, volume and diameters were developed andincorporated 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 entire growth period. The weighing system can also be applied to measure plant growth as an independent system. Fig. 8 shows the 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 analysed in correspondence with the plant geometric

features obtained from the imaging system allowing derivation of plant growth model under various controlled environmental conditions. This plant growth measurementsystem provides a non-destructive and real-time processingapproach over the traditional measuring methods. Furthermore,the automation feature of the system enables the systemto gather a large number of plant measurements easily. Hence, the system is an efficient and practicable tool to enhance the growingenvironment parameters tuning and optimization in a plantfactory environment.

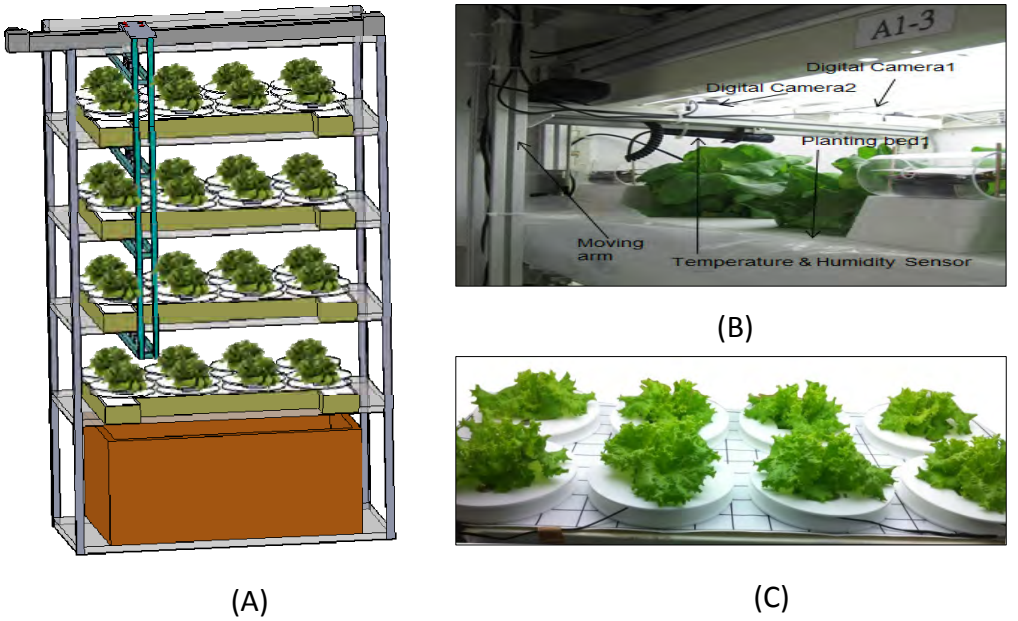

Fig. 8.The non-destructive plant growth measurement system. (A) Schematic diagram of the system, (B) the imaging system integrated with temperature and humidity sensors, (C) the plant weight measurement devices.

4.6 Business models of PFALin TAIWAN

PFALcan be an eye-catching point for it is new to general public and features/merits of PF attract environmental concerned and health concerned consumers. However, without proper business model, it is still highly possible a cash-trap if not considered thoughtfully. There are various types of business models being tested in the market of Taiwan.

The product can be the plant itself such as in the forms of a whole plant, loose leaf or babyleaf. The way to present the product is very important, such as the way of packaging, a sealed soft plastic bag, a soft plastic bag with tiny holes or a sealed hard plastic box. Different packaging method related to different story you expressed to the customers. It is a product no need to wash before eat or just similar to products grown in greenhouse? It

is a locally made not imported is also important issue to emphasize. Some also provide with salad dressing, the tastefulness of the dressing is also of great importance. One common thing is that the packaging bags and boxesare normally well designed to make it much more pleasant in the appearance compare with traditional agricultural products.

The sale channels can be membership based, through the web site, within the company or to the local community. It is important that one should limit their amount of sale through 3rd party. It is quite clear that sell the products through supermarket chain store (owned by others) can only be a temperate conduct, the shelf-charge is normally too high. That is to say, for PF product, B2C is much favorable than B2B.

If the company can't sell all their products, other product-linewasconsidered. One company in Taiwan developed more than 10 kinds of processed products such as ice-cream, egg roll, bread, noodles, face mask, skincare soap, etc. It can also be served as nutritional additive in various forms such as juice, powder and tablets. Different kinds of vege-additives have different prices in same product. For example, noodles with butter-lettuce and with ice-plant cost differently.

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

A shop has PFAL in the back or in one side and have restaurant or stands selling organic products in front are popular business models in Taiwan. Such shops are normally chain-stores and located in various corners within cities

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

Some companies capable of constructing PFAL for others, most of them have a demo-site for potential customers to take a look for further consideration. Some successful company will have a demo-site with a more convincing scale normally at daily production of no less than 100 plants and need to be operated smoothly for more than several months. With an established sale channel is most welcomed. Unfortunately, few companies reach these requirements that made them less convincing.

Many PFAL related hardware providers such as LED providers, clean room constructors, AC system providers, hydroponics system providers, power supply providers and thermally insulated material providers, these companies started to build PFAL demo room and started to learn how to grow plants. To become a PFALturn-key provider is their common goal.

In short, there are several distinct business models under practice in Taiwan.

1. PFAL produces leafy greens for their own usage. For example, restaurant owners and corporation with more than 1000 employee.
2. PFAL produces leafy greens for web customers and members. Some company are quite flexible, they even exchanged membership with other health related organization such as Yoga club.
3. PFAL produces leafy greens and processed products with vege-additives.
4. PFAL produces leafy greens is an eye catching point but with other profit making means such as construction, chain-store selling organic dry foods.
5. Home appliance style PFAL module providers with demo room.
6. Home appliance style PFAL module providers with alliance in construction industry.
7. PFAL related hardware providers built PFAL demo rooms to sell their products and plan to become turn-key provider.
8. PFAL turn-key builders and consultants with or without PFAL demo room.

As mentioned above, thePFALs in Taiwan although small in scale, but are flexible and dare to try various business models. At present, some looks promising, some has been failed. Even the same business model, still some win some lose as same as other emerging industry.

5. CONCLUSIONS

The PFAL is booming in Taiwan. Number of booths attending the PF expo increased 3 times in 3 years. Without financial and policy support from the government, the private companies get involved with high motivation. The PF related NPO organizations were established, enabling the horizontal and vertical connection and integration of companies.

At present, there was no private agricultural organization involved in PFAL in Taiwan. Several farmers' associations were considered to convert their unused warehouse to PFAL, but finally drop the idea. High initial cost was the first concern, difficult to find quality workers and manager to run the PF is another concern. It is quite true that at least at present, number of qualified managers and quality workers are not enough in the PFAL industry of Taiwan. Besides academic training in undergraduate and graduate schools of Taiwan, our team also offer 30 hours workshops twice per year and up to now, more than 400 people were trained, but less than 10% of them really get involved in the business afterward. To train qualified managers and quality workers for PF industry is an issue need to be taken care to enabling the worldwide business opportunities.

Many companies got involved with a keen eye looking at the business opportunities of the turn-key projects. However, some failed to proof that their system can grow quality plants efficiently. It was also sad to found that some companies consideredPFAL an opportunity to make quick money which lead to law suits and public confusion. Up to now, all the so-called international turn-key projects, around 10 PFALs built by Taiwan PF companies, are all in China.

Some consumers questioned about using artificial lights and hydroponics. Not nature, all chemicals were frequent challenged complains three to four years ago. Public awareness, food safety problems, environmental problems and frequent media exposures of PFALhelp consumers to learn about the technologies, appreciate the technologies and willing to pay extra money to buy products from PFAL.Nevertheless, to bring down the cost, increase the value, increase the suitable varietiesto be grown in PFALare tasks to be done. PFAL will be co-exists with organic agriculture and traditional agriculture.With no doubt, PFAL can also play key role in urban agriculture, in smart / intelligent city.

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