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Present status and future outlook of plant factories in Japan

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Abstract: Plant factories for the steady production of high-quality vegetables year round, and which can be divided into solar and artificial-light types, have recently been expanding in Japan as trigged by a report by a collaboration study group in 2009 and the Great East Japan Earthquake in 2011. Common solar-type plant factories with mulch-span roofs are often difficult to construct in the northern areas of Japan, especially along the Japan Sea coast, because of limited sunshine duration and heavy winter snowfall, while artificial light-type factories are more promising in this region although high running costs due to electricity bills for irradiating plants and cooling the room often hinder the promotion of such facilities. The use of LEDs has recently increased in artificial light-type plant factories, but fluorescent lights are still predominant for economic reasons. Generally only small plants can be grown commercially in artificial light-type factories and the light intensity reaching the lower leaves decreases continuously as the stem of the plant elongates, deteriorating light use efficiency. Flexible organic electroluminescent devices able to cover the whole plant when irradiation is required and that can easily be applied/removed like a plastic film are expected to be introduced in both types of plant factories.

1. Introduction

Highly systematized greenhouses for plant growth are called plant factories (PF) in Japan, and they have been rapidly increasing in recent years (Kobayashi, 2010; Nonami, 2010). PF are roughly divided into two types: the solar light-type (SPF) and artificial light-type (APF) (Murase and Fukuda, 2012; Kozai, 2013). Although both types are essentially the same as greenhouse cultivation, more advanced technologies have been adopted in PF to control growth environments. Japan's Ministry of Economy, Trade and Industry (METI) defines a PF as "a facility that aids in the steady production of high-quality vegetables all year round by artificially controlling the cultivation environment (e.g. light, temperature, humidity, carbon dioxide concentration, and culture solution), allowing growers to plan production" (METI, 2014).

The Netherlands is leading the world in the commercial use of SPF, and some well-known companies such as Hoogendoorn, Hortimax, and Priva export excellent cultivation systems to many countries, including Japan (Kozai, 2013). Compared to these advanced companies, the practical application of PF in Japan has just begun. Nevertheless, research papers and the use of PF have greatly expanded over the last few years. One of the triggers for the expansion of PF was the establishment of the "Plant Factory Working Group" of the "Agriculture, Commerce and Industry Collaboration Study Group in April 2009 in cooperation with MAFF (METI, 2009), who compiled a report describing issues to be addressed, as well as the support required for the promotion and diffusion of PF (METI, 2014).

The Japanese government appropriated approximately €100 million in the fiscal year (FY) 2009 as a supplementary budget to promote PF. Of this, approximately €36 million was spent on constructing and promoting advanced PF, and eight research facilities and 18 pilot plants were established in various areas of Japan, including seven universities (Kobayashi, 2010).

From a broad perspective, there are two ways to promote PF: one is to enhance the productivity of horticultural crops without relying on the experience of farmers, and the other is to allow the private sector to enter agro-industries.

2. Present economic status and agricultural production in Japan

Due to the impact of the financial crisis precipitated by the Lehman Brothers bankruptcy in 2008, the gross domestic product (GDP) of Japan decreased by approximately 7% during the five years from 2008 to 2012 (approximately € 3.7 and € 3.4 trillion, respectively) (Fig. 1) (IMF, 2013). However, Japan has been suffering from a long-term economic slowdown for an even longer period, often dubbed "the lost two decades." This long-term recession heavily impacted the private sector, for example

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construction industries, resulting in many unemployed workers.

Although agricultural production in Japan accounts for less than 2% of the GDP, production was sustained at a constant level during this period (approximately € 6.1 billion), showing that agriculture in Japan was not hit hard by the recession (Fig. 1).

Nevertheless, agriculture in Japan faces some difficult problems, such as a decline in the labor force due to a decreasing birthrate and the aging of farmers, limited farmland, high cost of production, and low productivity. However, such difficulties can also provide great opportunities for the private sector to enter into new business. Because of this, many companies in the private sector are now interested in entering agriculture, but it is also difficult for them to start new businesses due to legal restrictions hampering their entry into agriculture.

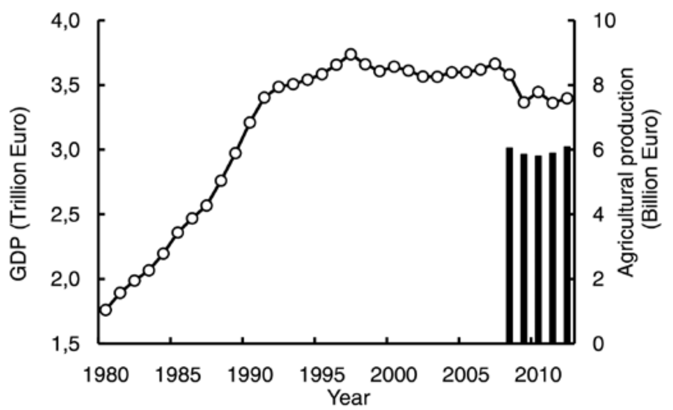

Fig. 1 - Figures for the GDP (1980-2012) and agricultural production (2008-2012) in Japan calculated using the IMF World Economic Outlook Database (2013) and statistics released by MAFF (2013), respectively.

3. Laws regulating the entry of the private sector into agriculture

Until 70 years ago, villages in Japan consisted of a few "zinushi" (landowners) who owned most of the farmland and a large number of "kosakunin" (tenant farmers) who worked on these lands (Council for Regulatory Reform, 2002). "Zinushi" lent the farmland to "kosakunin" to cultivate the land, and took some farm products, such as rice and beans, as "kosakuryo" (land rent). However, after World War II, farmlands in Japan were divided and distributed to each "kosakunin". This new policy allowed "kosakunin" to become land owners and saved Japan from food shortages during the postwar period. However, the area of distributed farmlands was too small for children to inherit. As the Japanese economy developed rapidly during the postwar period, many of these workers left the villages to find jobs in the cities, resulting in the aging of the farming population since the 1960's. According to statistics from Japan's Ministry of Agriculture, Forestry and Fisheries (MAFF), the total number of Japanese farmers in 2013 was 5.62 million, and 2.03 million of them (36.1%) were older than 65 years, which is higher than the percentage of over 65 years of the total population (24.1%) (MAFF, 2014).

Aging of the farming population rapidly decreases the production of agricultural products. Therefore, the Japanese government is now aiming to expand farm management by consolidating farmlands to develop efficient and stable large-scale farm management to improve agricultural productivity and stabilize production. However, such an integration of farmland has not yet given results because many farmers are still eager to possess their farmland as a property or as a means to earn capital gains by using it for alternative purposes (Council for Regulatory Reform, 2002). In addition, the "Agricultural Land Law" and "Agriculture Promotion Law" which were implemented in 1952 and 1969, respectively, work as a barrier when the private sector wishes to enter into agriculture, because they prohibit persons other than farmers from acquiring any farmland. Even if a farmer tries to repurpose his farmland, he has to send application forms with opinions from the Agricultural Committee located in each village, town, or city to the governor of each prefecture who is authorized to give permission through the committee. On the other hand, there is almost no restriction on the sale of horticultural crops, which will enable the private sector to enter agriculture if such companies grow horticultural crops on company-owned land, although the fixed property tax on farmland is considerably lower than that on commercial or industrial areas.

Another way for the private sector to enter agriculture is to finance agricultural corporations, but it will also be difficult to increase the flow of investment without improving the circumstances of corporate entry into agriculture, such as the further liberalization of corporate entry through farmland acquisition (Aritsubo, 2003).

For all these reasons, intensive cultivation of vegetables using company-owned factories and lands is possible for the private sector trying to enter agriculture. Also, chronic recession affecting the private sector associated with cutbacks in public investment leads to disused equipment, land, and available workers, all of which can also be directed by the private sector toward agriculture.

4. Characteristics of greenhouse production in Japan

In Japan, rice production was responsible for the highest sales among agricultural products until 1986, but both horticulture and animal husbandry increased thereafter as the price of rice decreased. At present, the sum of vegetable and flower production accounts for approximately 30% of the gross product, which is greater than rice production and almost the same as animal husbandry (Fig. 2).

Greenhouses have made a marked contribution to increasing the sales of these horticultural products, and the total area of greenhouses in Japan is now approximately

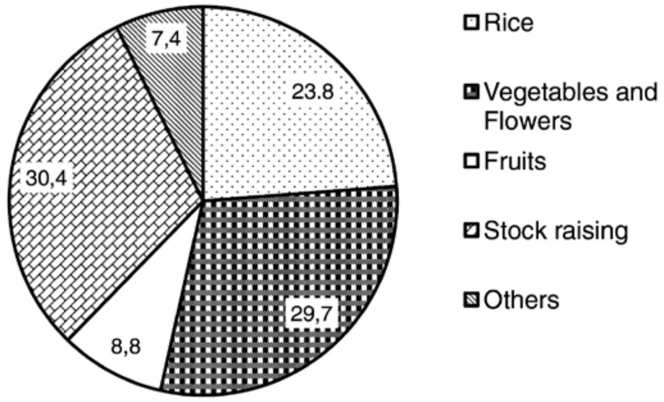

Fig. 2 - Proportion of each sector for total agricultural production in 2012. The pie chart was created using statistics released by MAFF (2013).

50,000 ha (Kozai, 2013). However, many of them are still plastic-film greenhouses smaller than 0.1 ha, and only 40% of them have a heating system installed. In addition, computerized environmental control systems have yet to sufficiently circulate commercially, which means that environmental control techniques in greenhouses still largely rely on the experience of farmers. As a result, the average yield of horticultural products from common plastic-film greenhouses still remains far lower compared to that of advanced greenhouses, where environmental management programs have been utilized to automatically optimize plant growth automatically. For example, the average yield of tomatoes in Japan is 60 t·ha^{-1}, which is only 13% of that in the Netherlands (476 t·ha^{-1}) (FAO, 2013). However, the introduction of computerized environmental management programs is not the only answer, cultivation of horticultural crops in Japan should be converted from empirical to computer-controlled methods to minimize the decrease in production due to the aging of farmers.

5. Introduction of SPF as a method to recover from the damage due to the Great East Japan Earthquake (GEJE)

The GEJE occurred on 11 March 2011, causing considerable damage to the country, including the agricultural sector. According to the data book of MAFF, the earthquake and subsequent tsunami affected approximately 24,000 ha of farmland in six prefectures located along the Pacific coast, which accounted for 2.7% of the total farmland in the region (Fig. 3, Table 1). Among the affected prefectures, the damage to Miyagi Prefecture was the greatest (10.7% of the total farmland), and it accounted for 60.6% of the total farmland area affected. In 2011, the Japanese government established the "Law on Special GEJE Reconstruction Areas" and special support programs to promote early recovery, such as the "GEJE Recovery Special Loan" program and "GEJE Recovery Emergency Guarantee" program. According to data from the Ministry of Finance (MAF), the central government spent approximately €137 billion on recovery from the GEJE during FY 2010-2012 (Sato, 2013). Miyagi Prefecture was a famous area for greenhouse production of horticultural crops such as strawberry, bell-pepper, and tomato, but many facilities were destroyed by the earthquake, and the subsequent tsunami caused serious salt damage to farmland, which resulted in only 33.3% restoration by 11 March 2012 (Table 1). Therefore, there is much expectation that the affected area will recover as a center for horticultural production

Fig. 3 - Major prefectures in Japan.

Table 1 - Distribution of farmland areas affected by the tsunami following the Great East Japan Earthquake on 11 March 2011 and their restoration

Prefecture	Farmland (ha)	Affected area (ha)	% of affected area	Restored area (ha)[z]	% of restored area
Aomori	156,800	107	0.1	101	94.4
Iwate	153,900	1,209	0.8	269	22.2
Miyagi	136,300	14,558	10.7	4,855	33.3
Fukushima	149,900	5,927	4.0	549	9.3
Ibaraki	175,200	1,063	0.6	958	90.1
Chiba	128,800	1,162	0.9	1,162	100.0
Total	900,900	24,026	2.7	7,894	32.9

[z] Restored area on 11 March 2012.
Table created from databases of MAFF 2011 and 2012.

by introducing large-scale SPF (Ito, 2012), and some facilities have already started running commercially (Fig. 4).

Fig. 4 - A solar-type plant factory constructed in the area affected by the Great East Japan Earthquake that occurred on 11 March 2011.

6. Present and future of SPF in Japan

The productivity of SPF largely depends on light conditions. In this regard, weather conditions in Japan are often a big barrier to introducing SPF. For example, the total duration of sunshine a Pacific coast area such as Kochi, Aichi, and Shizuoka Prefectures is 2,115-2,158 h per year (5.8-5.9 h per day), while that on the Japan Sea coast such as Akita, Aomori, and Yamagata Prefectures is 1,490-1,600 h per year (4.1-4.4 h per day), 69-76% of that on the Pacific coast (Fig. 3 and Table 2). When the duration is divided into summer (April to October) and winter (November to March), the former length does not differ much between the two regions (5.5-5.8 vs. 5.2-5.5 h per day for Pacific coast and Japan Sea coast, respectively), while the latter length on the Japan Sea coast (2.3-3.3 h per day) is only 36-56% of that on Pacific coast (5.8-6.4 ha per day). Moreover, the Japan Sea coast receives far more snowfall compared to the Pacific coast (377-669 vs. 0-16 cm per year on the Japan Sea coast and Pacific coast, respectively) (Table 2). Although SPF are usually multi-span type glasshouses with small roofs (Fig. 5), such structures of-

Fig. 5 - A multi-span type glasshouse with small roofs constructed in Tsukuba City, Ibaraki Prefecture.

Table 2 - Comparison of seasonal duration of sunshine and total amount of snowfall between Pacific coast and Japan Sea coast

Month	Monthly duration of sunshine (h)					
	Pacific coast			Japan sea coast		
	Kochi	Shizuoka	Aichi	Akita	Aomori	Yamagata
Jan	189.9	204.6	169.1	37.7	47.8	80.0
Feb	176.9	187.1	174.3	65.5	72.3	99.1
Mar	191.9	193.7	199.0	117.6	123.0	136.7
Apr	195.4	188.1	198.1	165.9	175.3	170.0
May	185.2	182.1	192.4	175.9	189.7	186.6
Jun	134.2	129.3	146.4	171.4	174.6	159.3
Jul	174.2	157.5	166.6	146.8	154.1	145.2
Aug	206.8	202.6	200.7	184.9	177.2	171.5
Sep	168.3	159.9	159.7	153.4	156.0	135.1
Oct	180.7	164.2	173.4	145.2	149.9	135.4
Nov	166.2	173.0	163.4	81.1	84.2	101.5
Dec	188.2	202.5	171.9	44.1	49.1	76.7
Jan-Dec	2157.9	2144.6	2115.0	1489.5	1553.2	1597.1
	Daily duration of sunshine (h)					
Apr-Oct	5.8	5.5	5.8	5.3	5.5	5.2
Nov-Mar	6.1	6.4	5.8	2.3	2.5	3.3
Jan-Dec	5.9	5.9	5.8	4.1	4.3	4.4
	Total amount of snowfall (cm per year)					
Jan-Dec	1	0	16	377	669	426

Table created from the database of the Japan Meteorological Agency in 2013.

ten cannot withstand the weight of heavy snow, especially in northern Japan. Therefore, APF and not SPF are more valuable from a commercial aspect along the Japan Sea coast of northern Japan.

7. Present and future of APF in Japan

Pioneering studies of plant growth using artificial light began as early as the 1920's (Harvey, 1922), and in the 1960's a useful book on artificial light for the production of horticultural crops was published (Canham, 1966). In Japan, vegetable production using artificial light has been studied since the 1970-80's, mainly in the research laboratories of MAFF and universities, and the results have largely contributed to clarifying the mechanisms of flowering, photosynthesis, carbohydrate partitioning, etc., under controlled environments (Nishizawa and Shishido, 2013). However, the results were not effectively applied commercially (Hashimoto, 2012). One of the pioneering examples of APS was the TS-farm of Kewpie Co., Ltd., constructed in Ibaraki Prefecture (Fig. 6), where leafy vegetables have been produced since June 1986 (Sekiyama, 1994). On this farm, triangle panels were arranged in an environmentally controlled facility and high-pressure sodium lamps and spraying hydroponics were used for cultivation. Another example of a pioneering APS was the "Rotary lettuce production facility" of Hitachi Co., Ltd., which was exhibited at the International Exposition, Tsukuba, Japan, 1985 (Takatsuji, 2009).

Although approximately 100 APF are functioning commercially in Japan now, many of them have been used for the cultivation of leafy vegetables such as leafy lettuce, while higher valued crops such as strawberry have been grown only in a few facilities (Kozai, 2013). Moreover, lighting systems of commercial APF still largely rely on fluorescent lights, which have the problem of heat accumulation in the plant during irradiance because of a low and high conversion efficiency from electrical energy to photons and heat, respectively (Hoshi *et al*., 2010; Takatsuji, 2010). Therefore, the cost for electricity to cool the facility is often more than 50% of that for irradiating the plants (Kozai, 2012; 2013).

Fig. 6 - TS-farm constructed by Kewpie Co., Ltd., in Ibaraki Prefecture.

Because there is marked potential to overcome the disadvantage of fluorescent lights by using LEDs (Massa *et al*., 2008), studies for the cultivation of vegetables using this light source have also expanded widely in Japan (Watanabe, 2011), but the commercial use of LEDs is still very limited mainly because of the high cost (Kozai, 2013). Even if the price of LEDs decreases to that of fluorescent lights, some difficulties still remain regarding the expansion of APF in terms of management. One of the intractable problems is that only small low-value-added crops are available to grow in such facilities. To solve this problem, studies to add value to the crops have been conducted, for example high-level antioxidative properties (Kozai, 2012; 2013), low potassium content (Suzuki, 2013), etc. by altering growth environments, or to cultivate more valuable crops such as seedlings (Yokoi *et al*., 2007), medical plants, genetically modified plants (Usami, 2011), etc.

However, such studies may come up against a limitation in the near future. While almost all horticultural crops can be grown in SPF, some which elongate longitudinally are still very difficult to grow in APF because the light intensity is theoretically inversely proportional to the square of the distance. Therefore, the light intensity reaching the lower leaves decreases continuously as the stem of the plant elongates. Longitudinally arranged fluorescent lights, comprising a line of corded LEDs in the plant canopy, and the utilization of laser diodes have been tested to solve this problem (Takatsuji and Mori, 2003), but these methods often aggravate working conditions for growers. One possible solution is to utilize organic light-emitting diodes (OLED) which emit light in response to an electric current using an emissive electroluminescent layer with organic compounds (Tang and VanSlyke, 1987). Although the light intensity of OLED is still lower than that of other illuminants, a high-performance white-light display of OLED has been newly developed at the Faculty of Engineering, Yamagata University in Japan (Kido *et al*., 1995), meaning that small horticultural crops such as leafy lettuce and strawberry can be grown (Fig. 7). Flexible OLED devices are theoretically possible to rewind like a negative film. Therefore, it may be possible to improve the efficiency of farmers' work by hanging film-type OLED devices from the ceiling of greenhouses and covering the whole plant only when irradiation is required. Such an illuminant can be utilized not only in APF but also in SPF.

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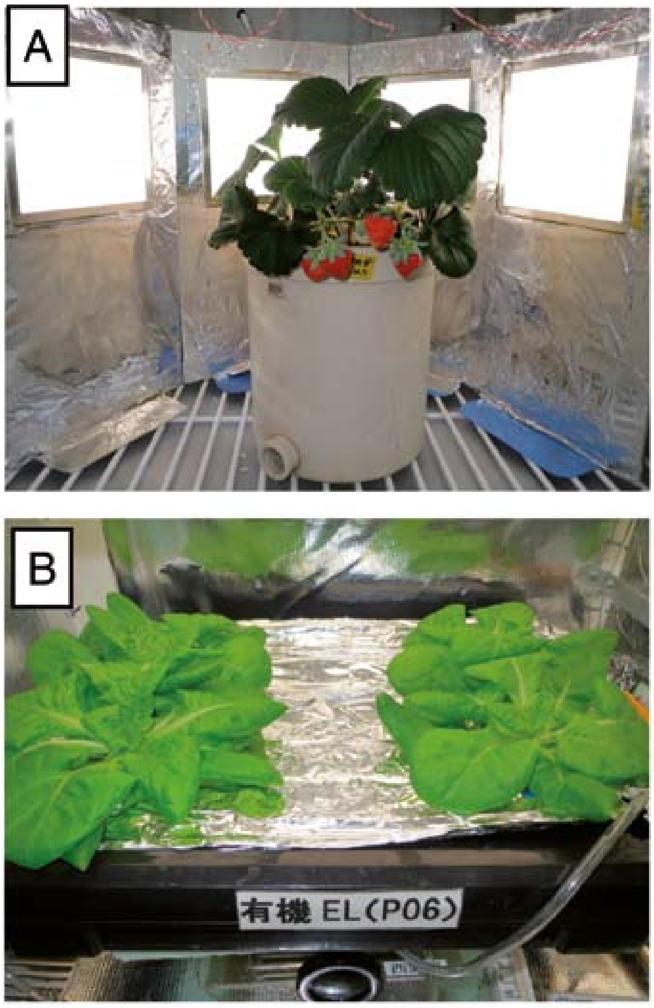

Fig. 7 - Strawberry (A) and leafy lettuce (B) grown under white-light organic electroluminescence display at the Faculty of Agriculture, Yamagata University.

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