Special Section 1

History, Current Situation, and Issues of Sensing, Environmental Control, and AI Application on Commercial Crop Production in Greenhouses

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Abstract

Research toward the application of electronic information and communication technologies to agriculture intensified in Japan from the 1980s with projects in areas, such as plant factories, plant biological information sensing, advanced environmental measurement and control systems, computer communication networks, and agricultural AI applications. Do the dramatic improvements in the cost performance of semiconductor devices in those days benefit even small and medium-sized greenhouse growers by bringing opportunities to improve labor and profitability through computerization? What are the remaining issues? Through what approaches may we expect them to be solved? This paper provides a comprehensive overview on the history, current situation, and issues concerning greenhouse farming systems based on the author's experience in this field.

Keywords：ICT, spread to horticulture, cultivation engineering, protected horticulture, smart agriculture

1. Introduction

The production of horticultural crops, such as vegetables, fruits, and flowers, in glass or plastic covered greenhouses is called protected horticulture. According to a survey conducted in 2018 by Japan's Ministry of Agriculture, Forestry and Fisheries (https://www.maff.go.jp/j/seisan/ryutu/engei/sisetsu/), 76.5% (by area) of greenhouse in Japan are small pipe greenhouses [steel pipe frames covered with plastic films], 58.8% (by area) are without artificial heating, the percentage of installed hydroponics is limited to 4.6% (by area), and the percentage of facilities with an advanced environmental control system is limited to 2.7% (by area). The distribution of the area size covered by advanced technologies and their deployment ratio at individual facilities are extremely more pyramid-like compared with other countries, particularly of advanced countries in the West. Research toward the application of electronic information and communication technologies to agriculture intensified in Japan from the 1980s with projects in areas, such as plant factories [(1)], plant biological information sensing [(2)], advanced environmental measurement and control systems [(3)], personal computer based on-line communication networks [(4)], and agricultural AI applications [(5)]. However, the deployment and spread of such technologies failed to make progress. They either continued to be used only at the several percent of the facilities at the top of the pyramid or were eventually disused. The chief cause is considered as the small sizes of facilities where such technologies could be introduced, which made the

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depreciation of capital investment difficult.

However, the dramatic improvement in the cost performance of semiconductor devices in those days virtually removed the barrier that prevented the installation of advanced technologies to minor greenhouses. At the same time, although slowly, the sizes of individual greenhouse and similar facilities are increasing, and we began to see progress in the deployment of systems for smart agriculture[6]. Also in the *Journal of IEICE*, the number of articles on ICT applied and smart agriculture has increased in recent years[7]~[10]. What are the issues that are yet to be solved to obtain benefit from the improvement in labor and profitability through the use of electronic technologies even the greenhouse growers at the base of the pyramid structure? Through what means may we expect them to be solved? This paper provides a comprehensive overview of the history, current situation, and issues of sensing, environmental control, and AI application in the area of greenhouse industry based on the author's experience of having been involved in the R&D of greenhouse crop production systems for nearly 40 years.

2. History

According to the literature, the history of protected horticulture facility use like greenhouse started in the ancient Roman Empire[11]. In Japan, the oldest description of the protected horticulture facility was on 1818[12], it was called "Tou-muro" caused by introduced from

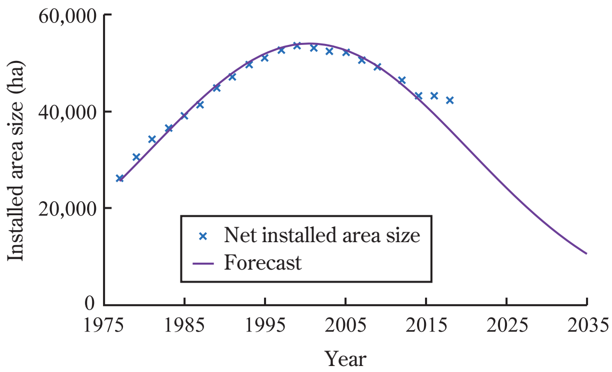

Fig. 1. Historical development and forecast of the total installed area of greenhouses in Japan This updates the latest data of a graphical representation in a paper (30) of a report on the state of installation of glass or plastic covered horticultural greenhouses from the Ministry of Agriculture, Forestry and Fisheries. The forecast was produced by the linear regressive extrapolation of the area size differentials in the statistics up to 2009.

China. For protecting plants in winter, they controlled the environment by heating the inside air by burning charcoal or by the use of fermentation heat. The first of the modern greenhouse to produce crops appeared in Japan in 1946 by the building of a two-hectare size, multi-span, steel-framed glass greenhouse on the former site of Chofu Airport[13]. It was built for the purpose of providing the occupying U.S. force personnel with fresh vegetables for salad. From the second half of the 1960s, greenhouse installation expanded quickly in Japan (Fig. 1) as the demand for vegetables for salad increased as the quality of life of the Japanese people improved, and the use of small pipe greenhouses became widespread as the cost for the plastic cover material like polyvinyl chloride. In that era, temperature control systems, such as ventilation window open/close motors, ventilation fans, electric hotbed wires, electric air heaters, pipe heating equipment by heavy oil boiler, heavy oil hot air heaters, using an automatic temperature controller were mainly use.

Plant production is based on the carbon assimilation by photosynthesis, which requires water, light, and CO_2 as materials. Since enzyme reactions are involved, the process is influenced by temperature as well. So, we have always paid attention to irrigation, daylight, shade, and coldness/warmth. Through the agricultural work of preparing soil and fertilization, we also considered the important supplementary nutrients of fertilizers. However, CO_2, contained in the atmosphere at the concentration of a mere 0.04% and unrecognizable by our senses, was neither measured nor artificially administered in the

Terminology

NDIR type "NDIR" stands for nondispersive infrared. NDIR type sensors serve as concentration sensors, for example, as they sense the absorbance of infrared rays of a particular wavelength by certain gases.

Arduino Small, low-cost, general-purpose single-board computers that originated from a project in Italy in 2005. They are now widely used in the world as typical open-source hardware.

Isolated beds Plant culture beds isolated from the ground. They are normally used for hydroponics. In that case, the balances of substance and energy are determinable accurately by measuring their input/output of the bed.

Load cell Load cell is known also as a load transformer as it convers mass or torque into electric signals. When implemented as an electronic weighing scale, a strain appearing on a metal plate under the action of a load is measured using a strain gauge and the signal from the gauge is amplified using a bridge circuit.

history of agriculture during the last 10, 000 years but was left to nature until recently. It was only in 1966 when a CO_2 balance model for plants was first proposed assuming a half-closed ecosystem inside a greenhouse [14].

In the 1970s, rapid advancement of electronic technology, combined with the demand for saving energy that went up the cost in response to the oil shock, accelerated R & D of environment control techniques for greenhouse industry. Optimized control for maximizing photosynthesis [15], direct digital control by means of mini-computers [16], and other papers were published. By around 1985, when an International Science and Technology Expo was held in Japan (Tsukuba Science Expo), plant factories began to attract much attention as a promising approach to the industrialization of agriculture [17], and many corporations became involved. With the growing popularity of microcomputers, research toward the practical use of computer-based environment control systems made progress [18], [19]. As an example of an advanced multiple environment control algorithm implemented by a computer, a proposal was made to change the control setpoint of temperature by proportional to solar radiation intensity [20]. That is to say, the suitable temperature for the optimal photosynthesis and transport (translocation) of its product was realized for the purpose of increasing yields and saving the energy for heating. Since CO_2 sensors that could be used for feedback control were expensive, CO_2 enrichment control by time of day or by the feeding forward of solar radiation intensity [20] was practiced.

In the 1980s, with influence from the Fifth Generation Computer System project [led by Japan's Ministry of International Trade and Industry], many attempts were made toward the application of artificial intelligence (the forerunner of what is now widely known as AI) to agriculture [21]. Such attempts started with the development of knowledge base systems [22] that were then called expert systems, and ended with experiments in using artificial neural networks (ANNs) that adopted backward error propagation [5]. The results of such early research failed to spread because they did not take into account the nonlinearity, inertia, and chaotic nature that characterize biosystems [23] and tried to handle them as simple machines that would respond linearly, and because the cost performance of electronic equipment was not at a level that could be accepted by greenhouse growers.

As a result of agreements on agricultural products during the 1993 GATT Uruguay Round, international competitiveness began to be required of Japan's agricultural products. As the Japanese government in those days advocated the policy of strengthening the country through technological excellence, the Agriculture, Forestry, and Fisheries Research Council led a nine-year project from 1998 for promoting comprehensive R&D of agricultural information systems that would help improve Japan's competitiveness. Research was performed under the titles of "Basic Research toward the Development of Multiplication Information Based Production Support Systems" and "Development of Database Model Coordination Systems". Information technologies that could contribute to agriculture were sought, and active efforts were made to make use of them. Text mining, distributed objects, IoT, information platforms-the seeds were born of the various information technologies that are now the focus of R&D for smart agriculture solutions.

The ubiquitous environment control system (UECS) [24], [25] widely used today as an information platform for environmental measurement and control at greenhouses in Japan is among the products of the above-mentioned project. However, Japan suffered a long recession, which is often referred to as "the lost 20 years" as the aging of farmers progressed. The total installed area sizes of greenhouses decreased from 1999 (Fig. 1) as new installations became rarer, existing facilities became obsolete, the import of agricultural products grew, and the government terminated the subsidy for advanced agricultural technologies. This trend was followed by successive termination of the production and sales of related facilities and equipment, and the discontinuation of business by their manufacturers and distributors. This caused difficulties in the practical use and spread of various technologies that resulted from the earlier R&D programs.

3. Current Situation

3.1 Smart Agriculture Technologies Attract Attention

Plant factories, which represented agricultural industrialization around 1985, again began to attract attention because they were looked at as examples of joint ventures across the agricultural, commercial, and industrial sectors in the context of the government's policy on revising and following up new economic growth strategies that was approved by the cabinet in

September 2008. This trend, combined with the improvement in the cost performance of LED lighting, led to the practical implementation of artificially illuminated (fully controlled) plant factories[26]. However, the ratio by which the electrical energy put into artificial lighting is transformed into a product as it is chemical energy inside the plants by photosynthesis is presently less than one percent (more than 99% is wasted)[27], so lighting efficiency must be improved. Therefore, economically justifiable plant factories have appeared only outside the production of calorie-rich food production in areas, such as the production of seedlings and the production of sprouts and some other leaf vegetables for salad and garnish of cooking. Since governmental support as part of the national policy has almost ceased now, the initiatives toward the development and deployment of such plant factories became weaker.

The R&D of smart agriculture has intensified[6]. The advancement of semiconductor device manufacturing and microfabrication technologies quickly improved the cost performance of MEMS (micro electromechanical system) sensors, memory devices, and computation devices. The refocus on machine learning under the catch phrase of "AI" is a trend brought about mainly by the improved performance of computers. Moreover, the widespread use of wireless communication and the internet improved the cost performance of telecommunications. In the area of protected horticulture, the lowering costs of CO_2 sensors, which can be useful for the control of CO_2, and of humidity sensors, which can be useful for determining the vapor pressure deficit to estimate the gas exchange (stomata conductance) and the dew point temperature to control diseases, contributed greatly to the promotion of smart agriculture. A CO_2 sensor of the NDIR type (see "Terminology") that used to cost about 160,000 yen in 1990 is now available in a much smaller size at a price of around 8,000 yen. Similarly, a humidity sensor at a performance level good enough to be able to expect a service life of three years even in the harsh environment inside a greenhouse, which used to cost about 50,000 yen, is now as small as 2.5×2.5 mm in size and available at a price of about 700 yen (Fig. 2). The prices of such devices dropped so low that their costs became sufficiently justifiable if they were introduced to greenhouses that so far relied mainly on the measurement and control of irrigation and temperature to improve the efficiency of management[28], supposing that it helps improve revenue by 10% or more. As a result, the ratio of use of advanced equipment, which used to be low, gradually improved (Fig. 3), and the decreasing trend of the total area sizes of greenhouses in Japan is showing signs of abating (Fig. 1).

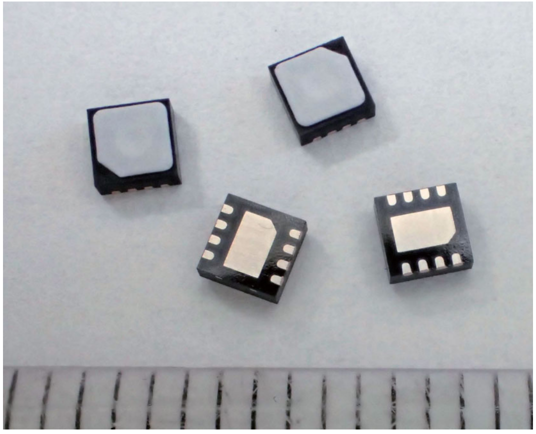

Fig. 2. Examples of humidity sensors used in greenhouses in recent years SHT31-DIS-F multi-pixel vapor sensors from Sensirion can measure relative humidity in the range between 0% to 100% (accuracy: +/−2%) and temperature in the range between 0 and 90 degrees C (accuracy: +/-2 degrees). The scale has dividing lines at 1 mm intervals.

To estimate what could be the present target for the cost of introducing smart agriculture, the author studied the productivity of greenhouse farming [in Japan] using the statistical information database (e-Stat) of the Ministry of Internal Affairs and Communications. In the 2018 statistics on agricultural and livestock industry sorted by the type of engagement, the author paid attention to the production of large-size tomatoes in greenhouses, noting that the total amount of production was relatively great. For that, the average statistics per a single squarer meter of planted area were reported as follows: the annual production was 10.3 kg, the annual labor was 1.19 hours, and the annual gross revenue was 3,040 yen. From the total area size of greenhouses in Japan, the average facility size per operator was calculated as 2,537 m^2 as of 2018. Therefore, per a single operator of a large-size tomato production facility in Japan, the average annual labor is 3,020 hours, and the average annual revenue is 7.71 million yen. Considering that the capital investment on a system that would help increase the revenue by 10% is to be depreciated in two years, the target cost of such a system should be about 1.5 million yen. How well the introduction of ICT might help reduce the labor hours through its contribution to labor saving and help increase revenue through its

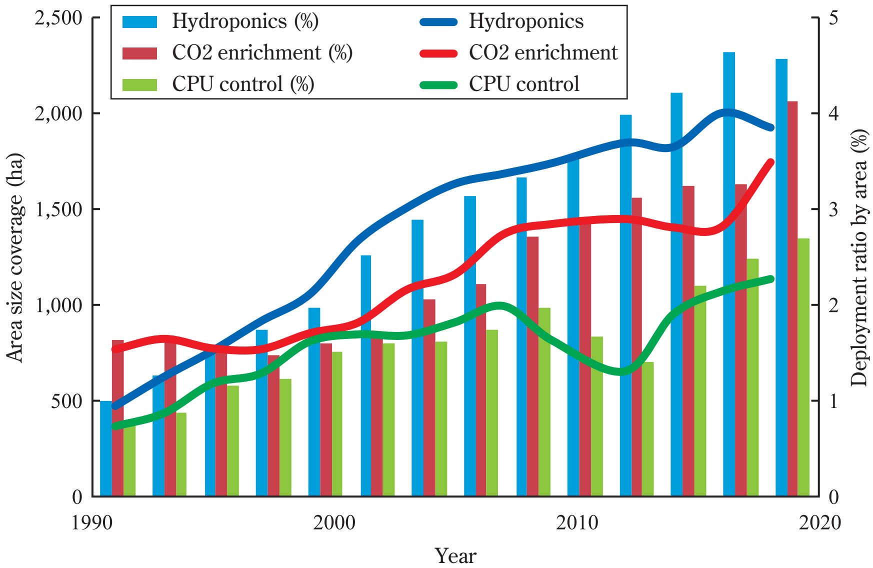

Fig. 3. Deployment of advanced equipment in Japanese greenhouses-area size coverage and deployment ratio From a report on the state of installation of glass or plastic covered horticultural greenhouses published by the Japan's Ministry of Agriculture, Forestry and Fisheries, the results of biannual surveys in the 1991-2009 period and the 2012-2018 period are shown in this graph. "CPU control" in the legend refers to advanced environment control.

contribution to productivity has to be clarified, then the acceptable levels of the system cost to be depreciated and the running cost of the system will become self-evident.

3.2 Introduction of ICT Contributes to the Downsizing of Profitability Greenhouses

For economic efficiency, it is customary to seek scale merit, such as the advantage of mass production. Compared with the Netherlands, where greenhouse farming has advanced to a high level, the average size of the greenhouse facility per operator in Japan is about 1/18[28]. Considering that, many projects for increasing the size of greenhouses have been launched in Japan. However, because of such adversities as the decrease in domestic demand due to the declining birthrate and aging population, difficulty in securing flat square land, difficulty in controlling diseases and pests due to particularities of climate and meteorological conditions in Japan, difficulty in fighting high temperatures, high costs of facilities and equipment from Japanese manufacturers, and other factors, it appears that the investment in and the building of large new facilities has been slow, failing to make smooth progress. In the Netherlands, where they succeeded in increasing yields as they continued to expand the facility size per operator, the unit prices of tomatoes dropped to a level that is one-third the prices in Japan because of the increase in supply and gradually led to a reduction in the total area size of greenhouse facilities. Since the operators are heavily indebted by investments in large facilities, finding themselves burdened by the need for repayment and covering interests, the income per labor hour does not differ much from cases in Japan ; thus, the expansion of facilities did not lead to the happiness of agricultural producers. The author has the impression that technological development oriented toward scale and quantity promoted the mechanical continuation of precarious management at a major scale that hardly allowed flexible changes in direction.

The promotors of improvement often claimed that, by promoting the R&D of advanced technologies for deployment at the topmost facilities and slackening regulations, the profits appearing on the part of the most advanced operators would be redistributed, bringing up the economic welfare of the whole. Technological development during the period around 1980 was pursued according to this philosophy of the trickle-down effect, but rather than lifting up the welfare of those who constituted the base of the pyramid, it cut them off. This served as one of the causes of the decline in the total area size of greenhouse and similar facilities in Japan from around 1999.

Reviewing the shift from mainframes to Tron[29], Grid, Ubiquitous, Edge Computing, the deployment of ICT appears to accord with the trend of downsizing through distribution. Projects, such as Arduino (see "Terminology"), that started from around 2005 made it possible for individuals to easily assemble gadgets using low-cost small single-board computers that are made available as open-source hardware. It was found that such devices could be used to configure UECS that failed to spread widely because of the high prices of dedicated circuit boards. In FY 2013, we started a project that aimed at developing such Arduino-based gadgets that would introduce ICT to small and medium-sized greenhouse operators in Japan, allowing them to benefit from advanced environment control capabilities comparable to the systems used in the Netherlands. In FY 2015, we succeeded in developing an open platform of an environment measurement and control system, which satisfied the need for low-cost UECS by small and medium-sized greenhouses in Japan and some other countries[30]. Together with corporations that develop and manufacture Raspberry Pi based systems, we conducted demonstration projects from FY 2016 in six prefectures of Japan. Installed in small and medium-sized greenhouse facilities in the respective areas and applied to crops and cultivation styles typical of the locality, by installed the low-cost UECS system, annual profit per greenhouse area size of 1,000 m^2 was more 175,000 to 934,000 yen than the before (https://smart.uecs.org/). The libraries and applications developed through the projects were made openly available as freeware ; they are downloadable from the mentioned website. Facility operators good at crafting might assemble their own systems by themselves. To help them do that, books were published[31]~[33] and seminars were held. As a result, more and more small and medium-sized greenhouse operators are deploying these systems. The deployment ratio (by area) of computer-based environment control systems, which decreased for a certain duration in the past, turned to an increase from around FY 2014, to which I think that our project contributed to a certain extent (Fig. 3). Rather than seeking the expansion of scale and production through the deployment of ICT, the author believes that we should address more realistic issues of today by seeking to improve the business sustainability of small and medium-sized greenhouse facilities in Japan that play substantial roles in the supply of greenhouse-grown vegetables and flowers.

4. Issues and Outlook

ICT-based sensing, measuring, and recording operations performed over time at greenhouse and similar facilities allow periodic and non-periodic conduct of data analysis, such as the study of variations over time, differences and occurrence probabilities through the use of trend graphs, and statistical processing. The next important target would be to develop a mechanism that helps expand the focus from a point to space in the collection of measurements. In the case of the high-wire type tomato production, about 2.5 plants are cultivated per square meter. While 25,000 tomato plants would exist in a greenhouse of one hectare, measurements from a sensor attached to only one of them is unlikely to represent the whole community. Such would be the situation if a cultivation media moisture sensor is used to take measurements of only one specific point in the media. However, the grid-like placement of multiple sensors at the production site would be costly and interfere with the work conducted in the greenhouse.

A brighter solution would be wider coverage sensing or mobile sensing. Wider coverage sensing may be achieved in the following manner. Supposing that isolation beds (see "Terminology") were used for cultivation, a load cell (see "Terminology") attached to one of the beds can collect information about the averaged media moisture in the bed for several tens of cultivating plants. The averaged photosynthesis rate may be estimated for the entire greenhouse using a CO_2 balance model[14]. For mobile sensing, mobile sensors that greenhouse farmers might carry around with them to connect to their smartphones should be developed to complement the conventional scheme of continuously collecting data using sensors installed in one place of the greenhouse. As they observe variations in the growth of their crops, greenhouse farmers know the spots in their greenhouses that require particular attention. They may bring mobile sensors for soil moisture and CO_2 monitoring to such spots and perform sensing operations there to study the cause of the problem and determine corrective actions. Mobile sensing by means of drones and similar devices is expected to make progresses. The use of drones and AI for measurements is almost exclusively discussed in connection with image capturing/analysis these days, but the author expects the application to mobile sensing and intelligent numerical measurement[34] as well.

As to environmental control, the maintaining of environmental conditions that would be optimal for photosynthesis and least stressful to plants was conventionally thought to be good. However, even when the environment inside a greenhouse is artificially controlled, a sudden change in the external meteorological conditions, for example, often produces conditions stressful to plants inside the greenhouse. Plants that are exposed daily only to favorable environmental conditions grow weak and may wither after suffering even minor stress as they lose the capability to fight stresses. Therefore, it is desirable that the plants' defensive strength, namely, their capability to fight stresses and tolerate changes in environmental conditions, is quantified through measurements and that they are given stresses at the appropriate level as part of the environmental control scheme so that such defensive strength may remain above the target level for the sake of more stable production.

The R&D of greenhouse farming in the 1980s sought high quality products, but from around the time when plant factories again began to attract attention, high yield became the primary goal. As the domestic demand for agricultural products is expected to decrease in the future, the author believes that now is a right time to redefine the goal. Particularly during a season when products from open-air fields are available, and the supply is abundant, there will not be any major advantage in continuing the mass production of fixed-quality products in greenhouses of the same or lower quality. Since such operation contributes only to the impoverishment of small horticultural producers through oversupply, greenhouses should establish a production management system that would avoid such a situation by changing crops or suspending operations. Greenhouses are to utilize the earth's meteorological resources in an amplified manner, and in this respect, they are unlike the absolute emulators of desired environmental conditions like artificially lighted plant factories. Rather than the seeking of globalized operations or the pursuit of the same quality of production all over Japan, the author recommends the pursuit of greenhouse farming that may profit the local community through the achievement of higher unit prices with measures, such as producing local specialties that are one grade higher in quality and extending the harvest time forward/backward, to be able to respond to off-season demand.

When agreements on sustainable development goals (SDGs) will be formulated at an UN-organized summit, greenhouse farming will be expected to seek not only economic efficiency but also be strongly motivated toward sustainability. Presently there are issues of the use of heavy oil-fueled heating, the non-recycle nutrient solutions in hydroponics, and the disposal of plant debris, waste culture mediums, and covering materials. R&D will be required for the administration of improvements through the assessment of energy and material balance, which may be performed using ICT and system sciences.

In terms of the value of production per a single person in Japan of the given profession, the average achieved by agriculture is 1/3.67 of the average of all industries. In the case of tomatoes, the efficiency of production in greenhouses is 2.49 times higher than production in open-air fields [35]. Many argue that agriculture in Japan is approaching a crisis because the population engaged in agriculture keeps on diminishing. However, if, without increasing the number of laborers, a system for the saved-labor production of tomatoes in greenhouses is established, allowing the greenhouse operators to maintain the current level of production in terms of value with labor reduced to 1/1.47, the production of tomatoes in greenhouses is transformed into an industry roughly as economically productive as other industries. Then, agriculture, being as attractive as other businesses, will attract new people, making the industry itself more sustainable. We could be in an era full of such opportunities. Much expectation can be placed on R & D on ICT in the future as a promotor of labor saving.

5. Conclusion

The author believes that the hopes placed on the deployment of ICT with dramatically improved cost performance herald the coming of wonderful times. On the other hand, as one of the causes for several of such enthusiasms in the past failing to give the expected results, the author identifies a rigid, vertical supply chain of technologies : development ＞＞ manufacturing ＞＞ sales ＞＞ consumption (by greenhouse operators).

When I was a student, professors told us, "You must look for research themes by making observations at field of farms". As mentioned in this paper, it often happened that the technologies that we developed in the laboratories based on our imagination of what could be helpful turned out not helpful at all at the real sites of agricultural production. Beyond outreaching activities, the author is strongly aware of the need for establishing an organizational framework for working together and thriving together to encourage farmers, system developers, and manufacturers to collaborate and discuss issues (a "Waigaya" method) from the very beginning of projects. As the next step, the author would like to create a mechanism like the Agricultural FabLab as a channel for making contributions to the development of sustainable greenhouse farming.

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