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Design of a plant factory suitable for Okinawa

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Abstract

A "Plant factory" is one of the advanced facilities for vegetable cultivation in an artificially controlled environment, i.e., temperature, humidity, and CO_2 concentration are controlled. Recently, it has become popular in Japan, USA, China and others. However, there are some problems to overcome before they become widespread. A project to develop a specific plant factory called the "Okinawa-type plant factory" has been funded by the Okinawa Prefecture. It addresses the severe environmental and social conditions of Okinawa. The main goal of the project was to reduce energy consumption by 30%. To achieve this, three methods were investigated using solar energy and LED lamps, since this plant factory used artificial illumination. Forty foot reefer containers were employed for the cultivation room, and insulation panels were partially used. Solar energy was used for lighting and air-conditioning. Solar energy was converted to thermal energy for air-conditioning using heat collecting panels. Hot water of 75-85 ^{o}C obtained by the collector was used for adsorption refrigeration. Sunlight was introduced in the cultivation room from the skylight windows. DC to DC system was also employed for photovoltaic utilization. The use of solar energy and LED lamps are effective to reduce energy consumption. A 30% reduction in energy use was achieved.

Keywords: Plant factory, Okinawa, Skylight, Solar collector, DC-driven

1. Introduction

Agricultural production strongly depends on the natural conditions. It causes instability of farm income and this is a serious issue for farm management, marketability and food security. Cultivation facilities such as green houses have been developed for many years to avoid the influence of severe natural conditions. A plant factory is an artificial cultivation facility with controlled temperature, humidity, light, CO_2 concentration and fertilizer. It is one of the ultimate cultivation systems. Normally, a plant factory consists of three parts, i.e., hydroponic culture system, lighting system and environmental control system. The hydroponic culture system and the lighting system are combined as a cultivation shelf. Since the cultivation shelf is made in more than one stage, it is possible to secure a large cultivation area even in a narrow space. Additionally, we can produce vegetables during any season and in any place. If we cultivate ten cycles using a five-stage shelf, the production volume reaches 20 to 30 times that of open culture. We can also expect stable production under a controlled environment suitable for vegetable production.

Now, construction of plant factories is booming in Japan. The government is promoting plant factories because it impacts not only agriculture but also industry. Many plant factories have been constructed since the Great East Japan Earthquake. However, there have been problems e.g., huge energy consumption for lighting and air-conditioning caused increased operational costs. Some plant factories have financially failed. So, it is very important to decrease the energy consumption of these operations.

Okinawa Prefecture is located in the southwest region of Japan, among many small islands. The climate of Okinawa is subtropical (Figure 1 [1]). Large areas of sugarcane and tropical fruits are cultivated [2]. The environment is not suitable for agriculture because of the small size, adverse climate and poor soil. Strong typhoons and severe drought are common in the summer. Cloudy weather and strong seasonal winds continue in the winter. Vegetables and flowers are cultivated in the winter and spring seasons when the temperature is mild. Shipping agricultural products to mainland Japan is done primarily in the winter and spring. This is the basic nature of Okinawan agriculture because vegetable production is not done at this time on the mainland. Vegetable production in the summer, May to October, is very difficult because of the severe natural conditions such as high temperatures, strong sunlight, typhoons and drought. Therefore, almost all vegetables are imported from the mainland during this season (Figure 2 [3]). Small islands are sometimes isolated from each other by typhoons and this often threatens food security. Additionally, long distance transportation of vegetables causes increased GHG emissions.

A plant factory is expected to provide an effective solution to these problems, because it can overcome such severe

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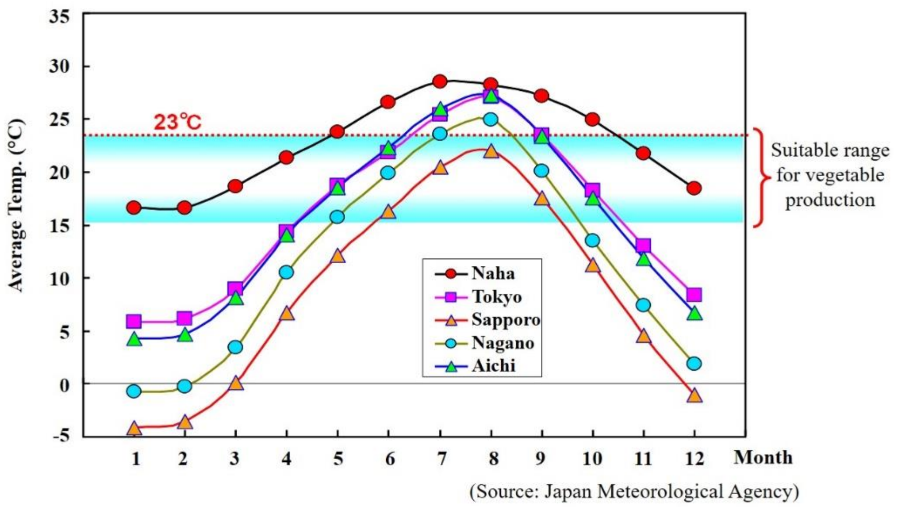


Figure 1 Comparison of average temperature in various cities of Japan (1971-2000). [1] Naha is the capital city of Okinawa Prefecture.

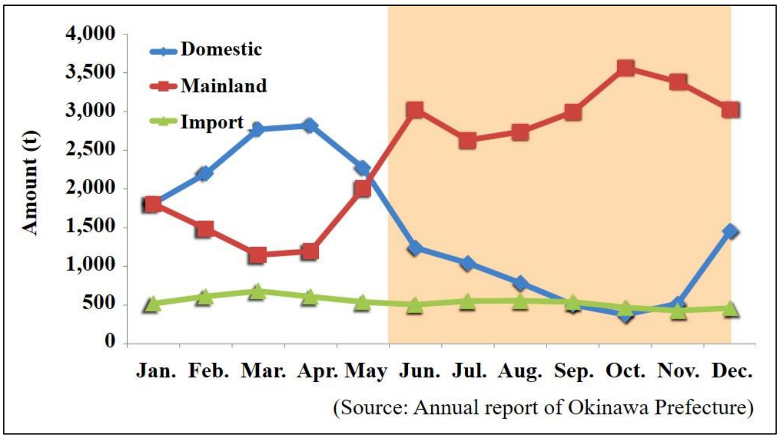


Figure 2 Transaction volumes of vegetables at Okinawa central wholesale market, 2012. [3]

cultivation conditions. It should be emphasized that an improved plant factory is necessary to reduce the aforementioned high energy costs. Therefore, we designed a new type of plant factory, namely the "Okinawa-type plant factory".

2. Basic design concept

Plant factories can be classified into two types according to their lighting systems. These are the complete closed & artificial illuminated and the sunlight illuminated types. The former is a real plant factory and the latter is a highly extended green house. As presented above, the plant factory is expected to bring a stable vegetable production system to Okinawa. Most facilities used on the mainland are hard to use on Okinawa since the natural conditions and societies differ so much [4]. We have to develop a new type of plant factory that is suited the special conditions of Okinawa. Reduced energy costs are the most important point in the design of a plant factory. The main target of the development project was to cut the energy cost by more than 30% compared to a conventional plant factory. Renewable energy was employed for reduction of not only energy costs, but also GHG emissions. To achieve this goal, sun light was used for illumination. Additionally, this cultivation method produces high quality fruits, vegetables, and local/traditional vegetables by controlling the light quality and amount of liquid fertilizer used.

3. Energy system

While the lighting system is a key of a plant factory, the energy system supports it. An energy system of a plant factory is shown in Figure 3. While the main power source is commercial electricity, we used renewable energy as much as possible. This included photovoltaics (PV) and solar thermal energy. A flexible sheet type PV was attached to the roof. Although the generated power was less than for a normal hard solar panel, it was able to avoid the damage due to the strong winds of typhoons. All of the generated power was consumed for the operation of plant factory. Since the power was connected to the commercial line, it was necessary to convert it from direct current to alternating current. This resulted in a loss of generated energy when we used LED lamps for lighting. If LED lamps were directly connected to the output of PV, we could avoid this power loss. The output of PV was usually unstable, so storage battery was necessary. A small size wind turbine will be also useful because it can be used to supplement the power generated by the PV.

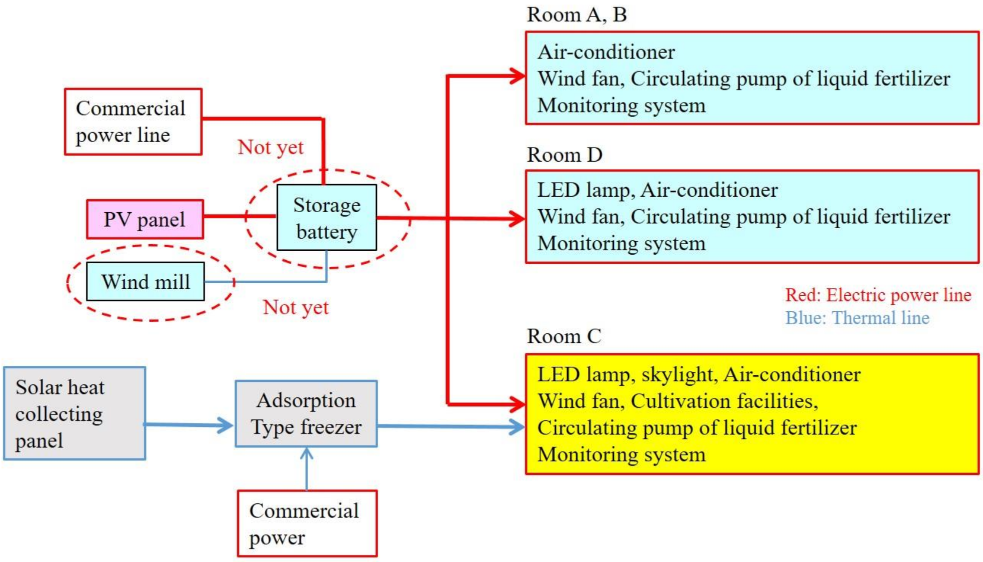


Figure 3 Energy systems for the plant factory based on the renewable resources.

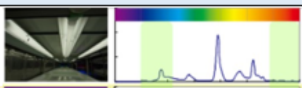
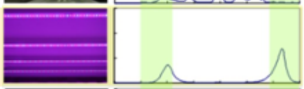
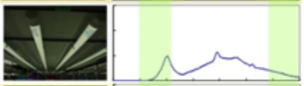
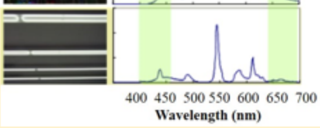
Light	Spectrum	Number (shelf $^{-1}$)	Light Intensity (μmol m^{-2} s^{-1})	Electricity (Wh shelf-1)
(FL)		36	214	1731 (100)
(RB-LED)		48	260	987 (57)
(W-LED)		48	141	1373 (79)
(W-CCFL)		48	134	1118 (65)

Figure 4 Lamp systems, spectra and performance.

3.1 Lighting system

A plant factory normally uses artificial light instead of sunlight. Artificial lighting was the bulk of energy consumption. Since fluorescent lamps are inexpensive compared to LEDs, their use reduces initial costs. However, operating costs, especially for electricity, become large due to their higher energy consumption. The quantum density of the light of an LED lamp is smaller than that of fluorescent lamps. Since the energy of the light is eventually turned into thermal energy, lighting increases temperature. Therefore, cooling of a cultivation room is important.

We tried to use some kinds of LED lamps for their lower energy consumption. R&D for LED lamps has been intensively done during recent years and their performance has improved remarkably. Various types of LED lamps for use in a plant factory have been developed and sold. Thus, their price has continuously decreased. Since the spectrum of an LED is quite different from that of sunlight, many studies have attempted to clarify its effect on plants. Much remains uncertain about the effect of LED lighting on plant growth. The quality and intensity of light and the lighting time suitable for vegetable growth should be investigated. In this study, four types of lighting systems, including LED and fluorescent lamps, were compared to determine which is better for vegetable production (Figure 4).

Instead of a completely artificial lighting system, we tried to use some sun light. A skylight window was installed in the roof of a cultivating room as shown in Figure 5. A skylight is a simple, low cost and effective lighting system. Strong sun light causes increased temperature. Furthermore, the intensity of light is affected by the size of skylight window. So, the design of a skylight is very important. One cultivation room (Room C) used four skylights. The size of each window was W100-L150 cm. They were made of 4mm reinforced pair glass. The vertical light intensity in the room was reduced to 50-90% of the intensity of direct sun light (2384 mmol m^{-2} s^{-1}). Furthermore, the intensity of sun light is unstable on cloudy and rainy days. We introduced sun light to supplement the LED lamps.

3.2 Air-conditioning system

Appropriate air-conditioning is a key requirement of a plant factory. The temperature of almost all leaf vegetable cultivation should be done within 18-25 ^{o}C. The heat in the cultivation room is derived from lighting and heat transfer from outside. The generation of heat by lighting can be

Figure 5 Lighting system using skylights.

reduced using LED lamps. Since the outside temperature of tropical and sub-tropical zones is always high, reducing heat transfer is an important issue. We employed a 40-foot refrigerated container as a cultivation room to reduce sunshine and the heat transfer from outside. Since the surface temperature increases by more than 50 ^oC on summer days, the container's surface was coated with a special paint. To reduce the heat transfer from the outside, we included thermal insulation boards in the structure of the container.

Two types of air-conditioners were employed, i.e., a heat pump and an adsorption type refrigerator. The latter was operated using hot water from a solar heat collector. We used a commercially available solar heat collector to produce hot water. Furthermore, we tried a new type collector using bagasse charcoal. Milled bagasse charcoal blending water efficiently absorbs solar energy [5]. The collector consisted of two plates 5 mm apart. One plate was made of glass or acrylic acid resin for transmitting sunshine. The blending water circulated slowly in the collector and the storage tank. The blending ratio of bagasse charcoal to water was 0.5% by weight. The temperature of water in the collector increased to 75-85 ^oC. The thermal energy of hot water was transmitted to the water through a heat exchanger. This adsorption refrigerator produced cold water at about 10 ^oC from hot water. The cold water was circulated to cool the cultivation room. A schematic of the air-conditioning system is given in Figure 6. The system is suitable for the climate of Okinawa because the summer season required much air-conditioning. Figure 7 shows sample temperatures. Hot water can be used for heating during the winter season, if necessary.

4. Development of pilot plant factory

A pilot plant factory was developed according to the aforementioned concepts. The structure of this plant factory is shown in Figure 8. The location of construction site is Nakagusuku Village, which adjoins the campus of the University of the Ryukyus.

1) Rooms

The plant factory consisted of four cultivation rooms, a working room and a pre-treatment room as described below.

Cultivation room: Three 40 foot refrigerated containers (L12-W2.5-H2.4 m) and one prefab room using insulation boards.

Working room: One 40 foot refrigerated container

Pre-treatment room: One 40 foot refrigerated container

2) Air-conditioning system

Cultivation rooms using refrigerated containers had two units of 2.2 kW (electrical consumption) air-conditioners in each room. There was a total 6 units.

Cultivation room using insulation boards had one 2.2 kW air-conditioner as a backup and one fan coil unit for cool water circulation from the adsorption type refrigerator.

The working room had one 2.2 kW air-conditioner.

The pre-treatment room had one 2.2 kW air-conditioner.

The total cooling capacity was 7 kW/unit*10 unit = 70 kW

3) Lighting system

The two cultivation rooms (rooms A and B) had fluorescent lighting: (32W+15W)*4 tubes*7units*4 shelves*2 low*2 containers = 21 kW (10.5 kW per room).

The single cultivation room (room D) with LED lights: Red, Red and Blue, White, CCFL, 24 W*4 tube*3 unit*4 shelf*4 low = 4.6 kW per room.

The cultivation room (room C) had skylights and LED lights. Four skylights equipped were installed in the ceiling of this room.

4) DC-driven cultivation shelf

The use of LEDs enabled remarkable energy savings. While the commercial electricity is AC, it is necessary to convert it to DC for the LEDs. Alternatively, the PV generated DC current so conversion is unnecessary. Considerable energy is lost in each conversion, so omitting it represents an energy savings. A DC driven cultivation system is useful since energy is stored at night and used in the day. The cultivation shelf driven by DC developed in this study is shown in Figure 9.

An LED unit can be raised to adjust the clearance between the LED lamp and the top of the crop [6]. The clearance keeps was kept constant with the growth of vegetables. This enabled more efficient use of light to shorten the cultivation duration by about three days [6]. The cultivation shelf was made of vinyl chloride tubing (Figure 9). In this case, the volume of liquid fertilizer needed was much less than if a large tank was used. The tube system prevented the germination of algae since the liquid fertilizer was not exposed to light, thereby reducing cleaning requirements. The cultivation tube system can be pulled from the shelf, making harvesting and transplanting quite easy.

5) Hydroponic culture system and CO_2 applicator

The hydroponic culture system consists of a pump for the circulation of liquid fertilizer, a blending tank and aquarium. A CO_2 applicator was used to maintain a 1500 ppm concentration to enhance the growth rate of vegetables.

6) Monitoring sensor network system

It was very important for the operation of the pilot plant factory to control environmental parameters such as temperature, and humidity, among others. Sensors were set on the cultivation shelf and in energy system (Figure 10). The collected data was monitored via the Internet. We could monitor the conditions of pilot plant factory at any time and place.

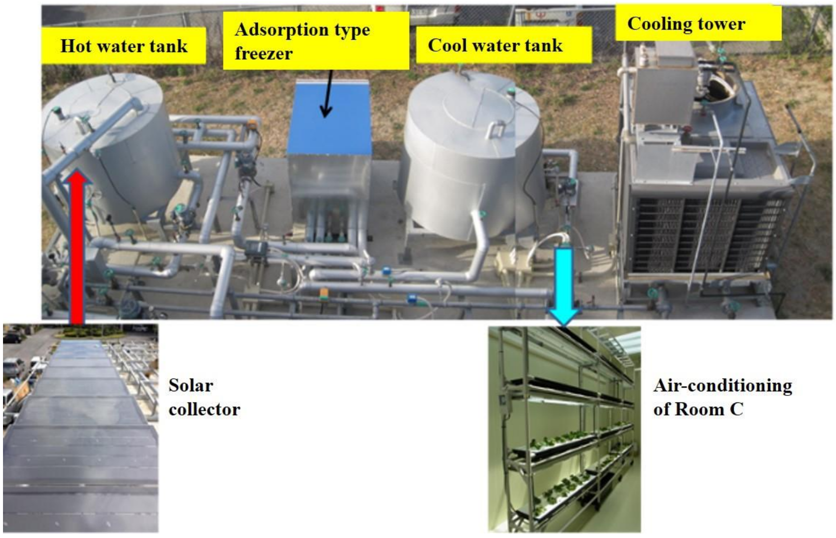


Figure 6 Air-conditioning system using hot water produced by the solar collector.

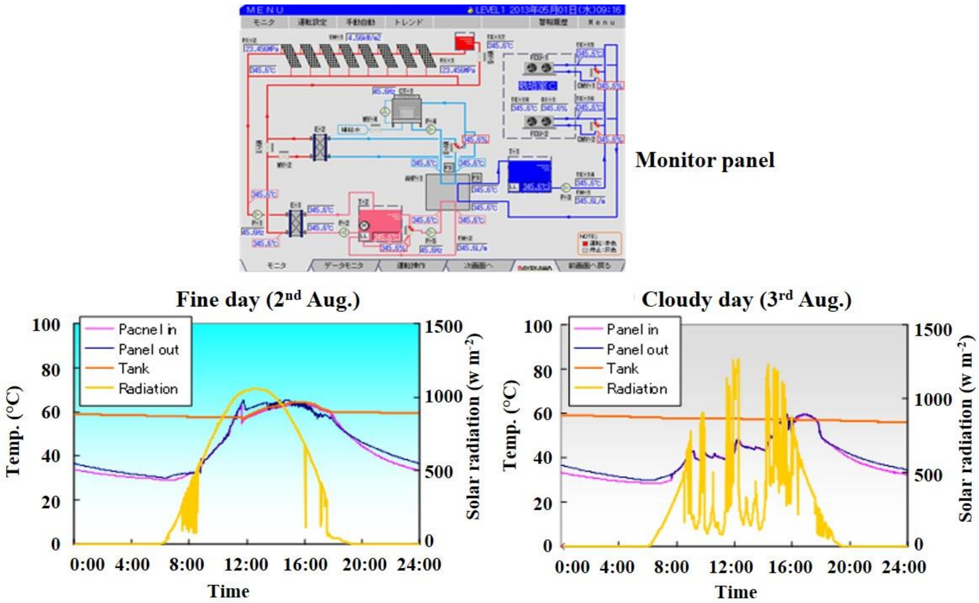


Figure 7 Solar radiation and temperature change.

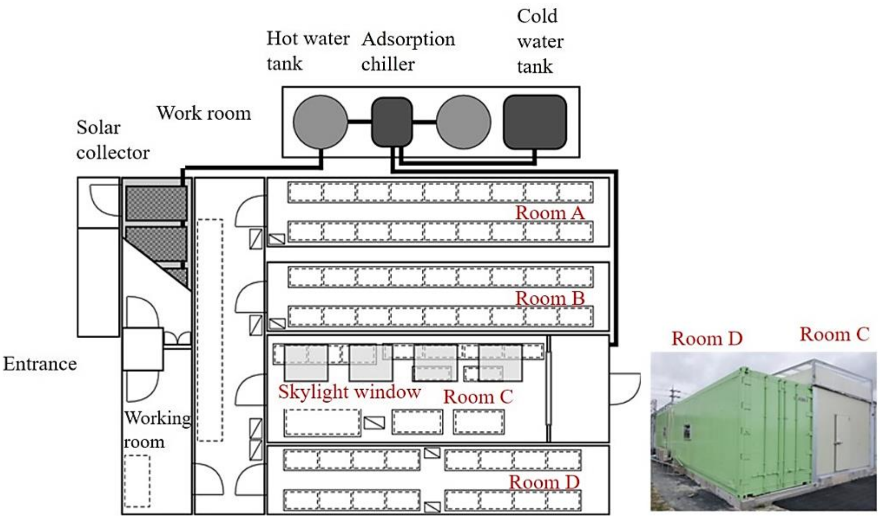


Figure 8 Developed pilot plant factory in Nakagusuku Village, Okinawa.

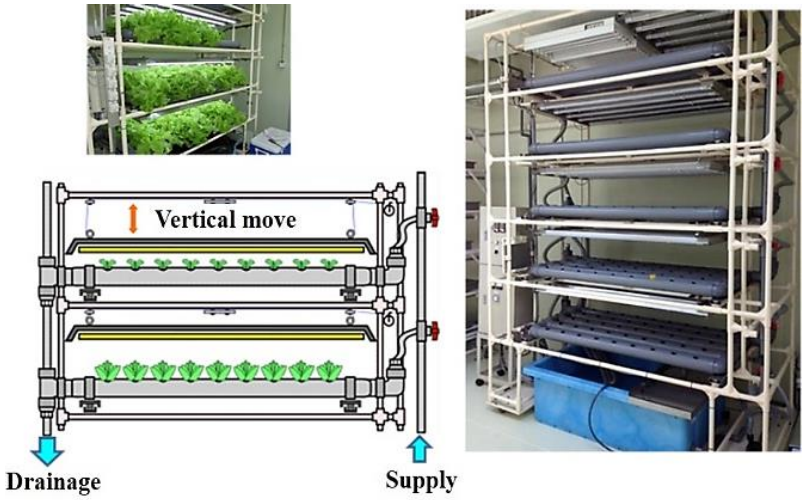


Figure 9 DC-driven cultivation shelf in Room C.

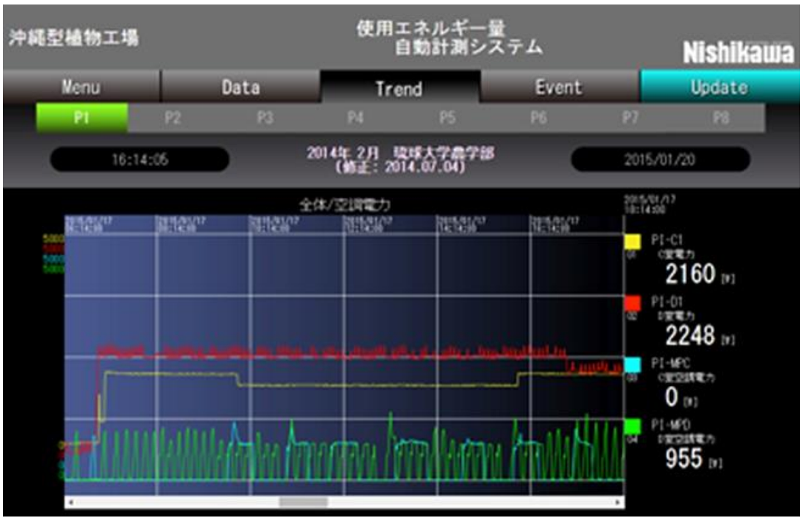


Figure 10 Monitoring system of the pilot plant factory.

Figure 11 Vegetable production in the pilot plant factory.

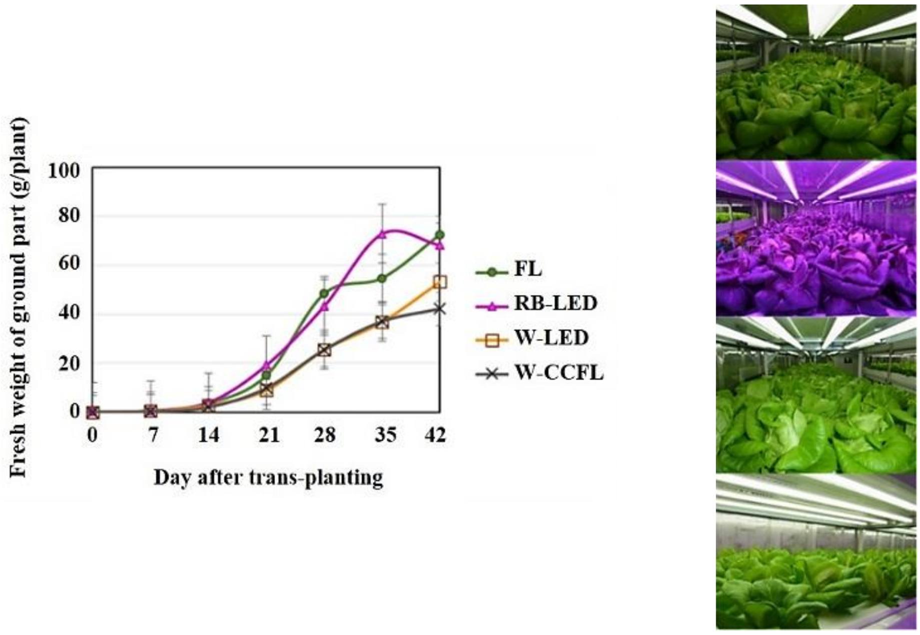


Figure 12 Growth of lettuce under various kinds of artificial lamps.

5. Cultivation test

Not only leafy vegetables such as lettuce were cultivated, but also strawberries were grown in this pilot plant factory. Figure 11 shows the vegetable production in the plant factory. Strawberries grew well. Some vegetable growth curves are shown in Figure 12.

6. Conclusions

A new type plant factory suitable for the conditions of Okinawa was designed and a test facility was developed. It used artificial lighting and sun light. Energy consumption was reduced by more than 30%, successfully achieving its objectives. Renewable energy was effectively used for lighting and air-conditioning. A new air-conditioning system is still being tested for improved system performance. Cultivation of high quality vegetables in a plant factory has now been achieved in Okinawa.

7. Acknowledgements

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