5. HIGH-EFFICIENCY FOOD PRODUCTION

Naoshi Kondo (Professor, Division of Environmental Science & Technology, Graduate School of Agriculture, Kyoto University)
Takayuki Ohba (Professor, Laboratory for Future Interdisciplinary Research of Science and Technology, Tokyo Institute of Technology)
Hiroyuki Ito (Associate Professor, Laboratory for Future Interdisciplinary Research of Science and Technology, Tokyo Institute of Technology)
Koji Kashima (Asahi Kogyosha Co., Ltd.)
Katsuro Fukozu (Laboratory for Future Interdisciplinary Research of Science and Technology, Tokyo Institute of Technology)

We propose a method that assumes eight items (rice, soybeans, sweet potatoes, potatoes, tomatoes, lettuce, cucumbers, and strawberries) cultivated on a lunar farm that are efficiently produced for six to 100 inhabitants. We were especially interested in the case of 100 people.

In this proposal, we first show the technology that is commonly applied to all eight cultivated items. Next, the cultivation style is determined for each production item. The optimum cultivation method for realizing the style, for example, batch type cultivation or a continuous method by moving the cultivation part, was roughly classified. The crop production process was divided into phases, such as sowing (planting), growth, and harvesting, and we propose growth/environmental monitoring items, specific sensing methods, and mechanization methods necessary to introduce automated work as much as possible in each process. Some of these elemental technologies are considered achievable by applying existing technologies. However, they also include methods that will likely require further technological improvements in the future, such as the development of drones and robots and the establishment of sensing methods.

5.1 Common technology

Cultivation is based on hydroponics that does not use soil. However, water is a valuable resource on the moon, and it is necessary to keep the water supply to the minimum for plant growth to avoid loss caused by the circulation of the culture solution and bias of nutrient components in the culture solution. Therefore, spray hydroponics using dry mist was adopted for crop cultivation in this report [1]. As a light source for photosynthesis, sunlight also falls on the moon's surface, but there is concern about the effects of exposure because of the lack of geomagnetic shielding of cosmic rays. Furthermore, on the moon, the day-night cycle is approximately 28 d, which is far from the biological rhythm of crops that have evolved on the earth, and there is a high possibility that it will hinder growth. Therefore, we decided to use LEDs as the light source. LEDs have wavelengths in the ultraviolet and infrared regions and can be effectively used as a light source for sensing, as described later. When monitoring growth, fluorescence imaging techniques may provide useful information across all cultivated items. It has a wide range of uses as an existing technology, such as photosynthetic activity that can be observed from the acquisition and analysis of chlorophyll fluorescence, detection of newly developed buds (growth points), and distinction between leaves and stems [2].

One of the most important core technologies for all crop production is image recognition technology using artificial intelligence. Because of the recent breakthrough in deep learning, image recognition accuracy after proper learning has surpassed humans [3]. The introduction of image analysis and recognition technology backed by artificial intelligence will be indispensable to accurately recognize the edible parts of the crop in order to perform reliable harvests on the lunar farm, and obtain information necessary for cultivation, such as the growth situation and the time of harvest.

In the following proposals for each cultivated item, we assume that the common technology mentioned is actively used.

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5.2 Cultivation methods for each cultivation product

In consideration of each crop's harvest efficiency, cultivation styles, such as the planar simultaneous harvest type and the multi-stage type, were determined, and the cultivation method satisfying that style was also determined. The cultivation method is also related to the shape of the cultivation device and is an important consideration that affects production efficiency, workability, and the finished crop quality. Table 5.1 below shows the cultivation method when each of the eight cultivation items is produced for the expected number of residents. If the estimated number of residents is six, it is assumed that all of them will be engaged in the work, but if the number of people is 100, we propose a cultivation method that can achieve high-efficiency production and a cultivation method that realizes it.

Another group estimated the acreage required for each cultivated item to produce a nutritionally balanced food for 100 residents, and that information is also shown in Table 5.1. It should be noted that this cultivated area is a numerical value for all cultivation on a planar surface without considering multiple stages for increasing area efficiency.

Here, the batch method refers to a cultivation method in which plants in a predetermined plot are moved or renewed all at once at harvest or replacement of all plants without moving the plants after sowing or planting. The continuous method refers to a method in which one plant or a small number of plants (supporting materials) move with growth, sowing or planting at regular time intervals, and harvest at similar intervals. Tomatoes and cucumbers are cultivated horizontally on a multi-tiered shelf with a flat spread.

Table 5.1. Cultivation regimes for each crop by number of supplies

Crop species	Six persons	100 people	Required cultivation area for 100 people (m^2)
Rice	Batch	Batch	4000
Soybean	Batch	Batch	2500
Sweet potato	Batch	Continuous	2250
Potato	Batch	Continuous	1000
Lettuce	Batch	Continuous	900
Tomato	Batch	Multilevel shelf	90
Cucumber	Batch	Multilevel shelf	50
Strawberry	Batch	Individual	550
< Common Items> Use solution cultivation (dry mist) and LEDs for lighting			

5.3 Division of growth process and appropriate monitoring items for each cultivated product

As the number of residents living in the lunar living space increases, it is necessary to increase production to support the population. Not all residents are engaged in food production work (agriculture); thus, we must realize a labor division, which must be done efficiently to produce food for many people in a labor-saving manner. Additionally, it is necessary to realize automation and mechanization by reducing the manual work that causes variation and errors as much as possible, because to ensure a stable supply of food, the yield must be planned and secured such that there will be a surplus with a certain quality and in consideration of stockpiling. Items to consider to achieve automation and mechanization include a mechanism that regulates the growing environment, but also the development of work machines such as robots and drones, and means and sensors that accurately determine the growth state and changes of plants, as well as the position of harvested products [4].

The table below summarizes the work and sensing items necessary from sowing or planting to harvesting for the eight crops that are expected to be produced, and judgment was added as to whether existing technologies can be applied or new technology development is required to achieve them.

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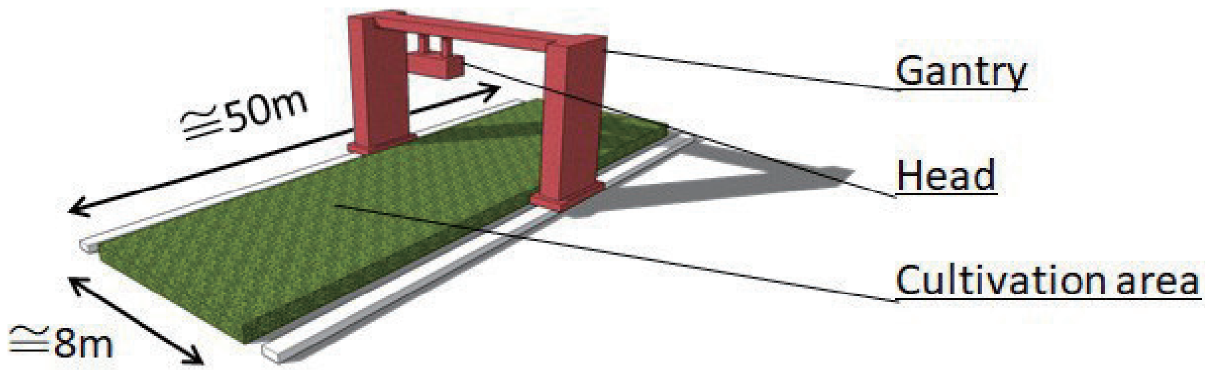
5.3.1 Rice (batch method)

Items Number	Process	Application technique	Existing/newly developed	Remarks
1.1	Seeding	Sowing using gantry; automatic seeding of two to three grains at a fixed pitch	Existing	Needs to be integrated into the gantry
1.2	Germination and growth confirmation	Image analysis (visible light/multiple wavelengths)	Existing	Need software development
		Photography (gantry fixed/fixed-point shooting/drone use)	New	
1.3	Lighting change method	Strain growth judgment and concentric LED irradiation	New	Requires image analysis
1.4	Determination of the appropriate time for harvest	Near-infrared spectroscopy image analysis (estimation of protein and water content)	Existing	
1.5	Harvest	Batch harvest with gantry connecting combines	Existing	
1.6	Post-harvest	Freeze-dry brown rice for conservation	Existing technologies	
		Hull the rice without drying it to make brown rice	New	Normally, hulling is not possible unless it is dried.

The required rice cultivation area is estimated as 4,000 m^2 (Table 5.1). It requires a large cultivation area compared with other plants, and it is thought that the benefits of mechanization can be substantial. Because rice is cultivated in one place from sowing to harvesting, it is efficient to improve the machine called a gantry that moves over the cultivation area, as shown in Fig. 1A, such that all work can be done automatically. A multifunctional head mounted on the gantry's arm conducts sowing, growth confirmation, harvest time determination, and harvesting work. As a plan to cover a cultivation area of 4000 m^2, we propose a system that can flexibly expand the cultivation area by grasping the cultivation part carried by one gantry modularly and combining them in a plane. Because it is based on cultivation using artificial lighting, it is possible to effectively utilize the area by configuring this module in multiple stages instead of simply being flat.

A)



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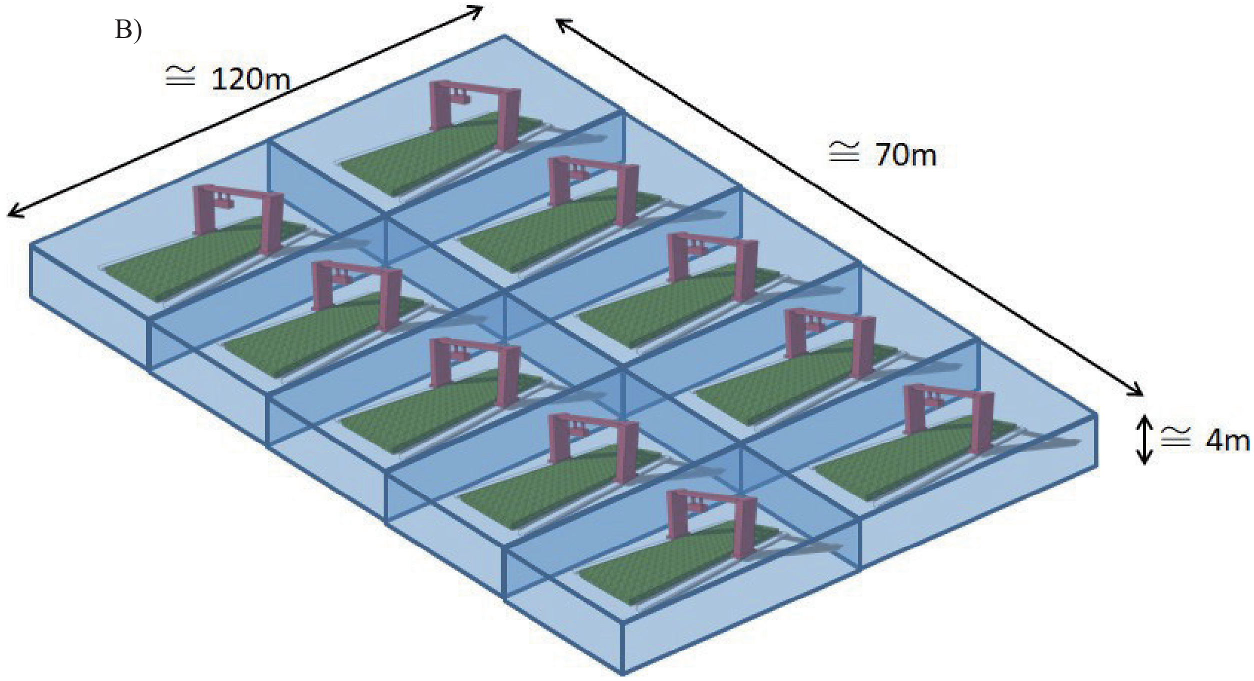

Fig. 5.1 Gantry type cultivation used in batch systems
A) Basic unit image and size of gantry cultivation equipment
B) Image diagram enclosed in individual modules for air conditioning, lighting, and multiple connections for 100 residents

Because rice requires a large amount of light for cultivation, it is necessary to use a powerful LED lighting system that can emit approximately 1,000 μmol/m^2/s as the effective photosynthetic photon flux density (PPFD) [5]. Meanwhile, there is concern that the spacing between the plants will not change during seedlings growth and maximum overgrowth and that unnecessary lighting will be applied when the vegetation is sparse in this cultivation method adopted from the aspect of sowing and harvesting efficiency of rice. Therefore, it is necessary to develop and introduce a lighting system capable of detecting each strain's horizontal spread by image judgment and change the irradiation range according to the size of the strain.

Non-destructive inspection using near-infrared (NIR) spectroscopic images is considered useful for determining the quality of grains and the optimum harvest time [6]. Combined with the information obtained from the fluorescence images mentioned in the section on common technology, it is possible to effectively monitor the period from germination to the rice harvest.

5.3.2 Soy (batch method)

Items Number	Process	Application technique	Existing/newly developed	Remarks
2.1	Seeding	Sowing using gantry; automatic seeding of two to three grains at a fixed pitch	Existing	Needs to be integrated into the gantry
2.2	Germination and growth confirmation	Image analysis (visible light/multiple wavelengths)	Existing	Number of leaves, abundance, number of flowers, length, diameter, and color
2.3	To determine the appropriate time for harvest	Image judgment	Existing	Color of the pod and degree of dryness
		Sound	New	Utilizing noise in the pod during drying period
2.4	Harvest	Batch harvest with gantry connecting combines	Existing	

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As with rice, soybean cultivation uses the batch method and cultivation equipment modules using a gantry. However, it is usually completely dry at the time of harvest, such that it is necessary to monitor dryness. Image analysis or directional sound wave sensing will be useful for this purpose.

5.3.3 Sweet potato (continuous method)

Items Number	Process	Application technique	Existing/newly developed	Remarks
3.1	Planting (cuttings)	Collect seedlings with an insect-type robot that cuts vines that have grown to a certain extent (day management)	New	
		Planting one seedling each	Possible with existing technologies	
3.2	Measurement of growth status	Image analysis (visible light/multiple wavelengths)	Existing	Software may need to be developed
		Application of automated chlorophyll fluorescence measurement	Existing	
3.3	Determine the appropriate time for harvest	Helmholtz resonance and imaging judgment	New	Is the ratio occupying the space required?
3.4	Harvest (leaf)	Robotic sampling	New	Insect-type robot use; if too much is removed, the potato will not grow.
3.4	Harvest (potato)	Possible if appropriate weight (volume)	New	Is there a sorting method for roots of non-edible parts?

It was estimated that a cultivation area of 2,250 m^2 would be required to supply an appropriate amount of sweet potatoes for 100 residents (Table 5.1), but continuous cultivation is a space-saving and highly efficient cultivation method. There is a possibility that the required cultivation area can be reduced if this method is adopted. The continuous cultivation method is a method with a cultivation device with a movable cultivation surface, such as a belt conveyor (Fig. 5.2). In places where the environment can be controlled to a certain degree, cultivation and harvesting are possible throughout the year, leading to leveling of daily work and consolidation of workplaces, such as for harvesting. Additionally, because the crops can be cultivated densely during the seedling period, the cultivated area utilization efficiency can be improved in combination with a method for adjusting between strains.

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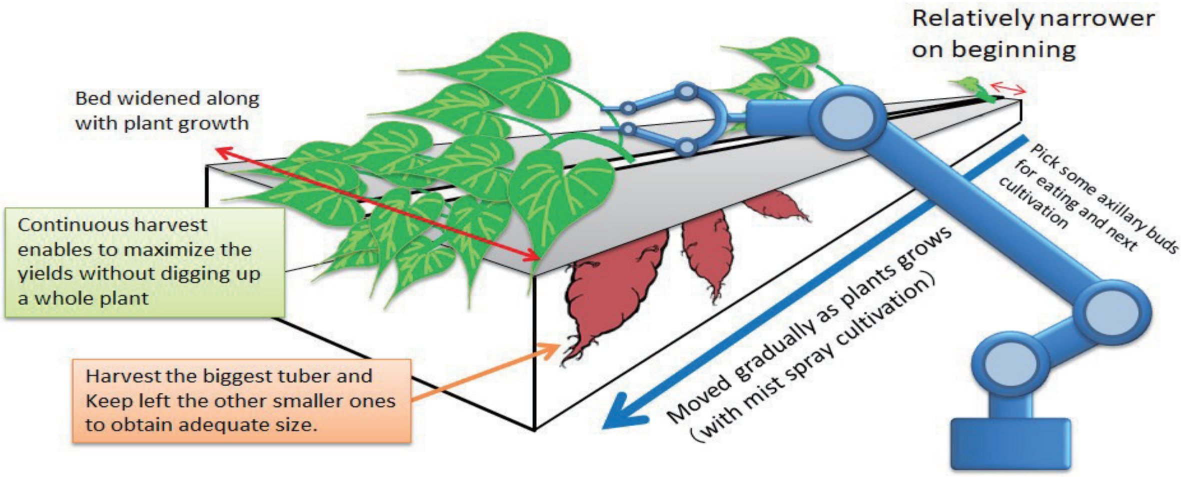

Fig. 5.2. Schematic diagram of a continuous cultivation system that expands cultivation range along with sweet potato leaf abundance

For example, because the daily weight requirement for sweet potatoes is assumed in this working group to be 150 g, 100 residents will eat 15 kg of sweet potatoes every day. Because sweet potatoes are expected to be harvested at approximately 2 kg/m^2, a daily harvest area of 7.5 m^2 is required. Assuming that sweet potatoes will be harvested from the start of cultivation after 4 months, 900 m^2 is required by simple calculation to continue harvesting 7.5 m^2 every day, but it is necessary to achieve the above-mentioned dense planting at the time of seedling establishment. The area is expected to be reduced by approximately half (Fig. 5.3).

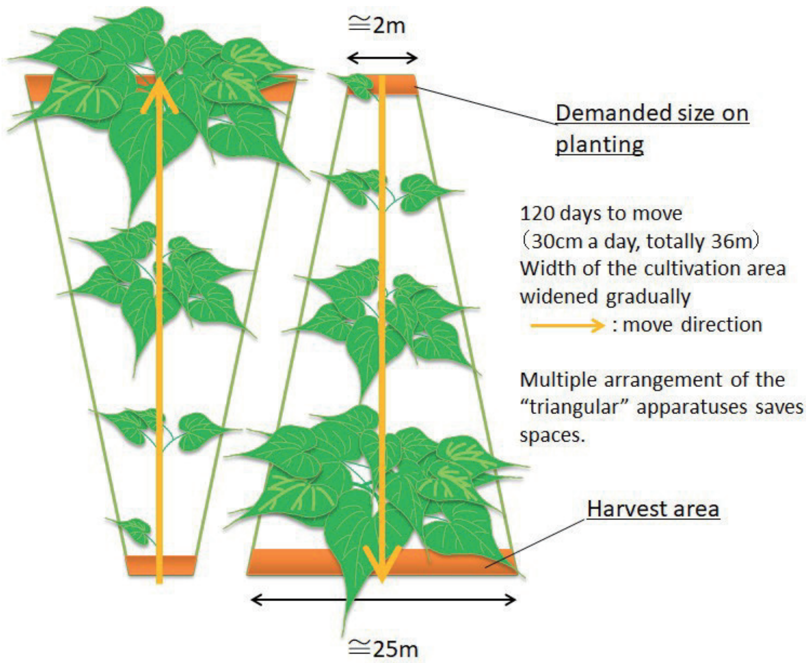

Fig. 5.3. Increase in the efficiency of the area used by inter-strain expansion in continuous cultivation

There are some techniques for widening the space between plants in hydroponics, but in the case of mist cultivation, which is the basic water supply style on lunar farms, if there is a gap, mist may leaks from it, such that it is necessary to develop a technology to adjust the spacing between plants while maintaining high sealing performance.

Because potatoes grow underground, we propose a technique that applies the Helmholtz resonance in addition to image analysis as a means to confirm growth in a non-contact manner. Helmholtz resonance is a phenomenon in

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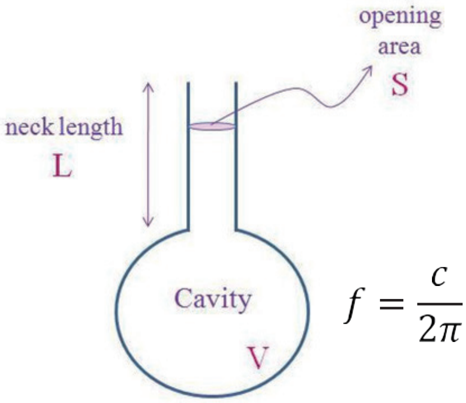
which sound is produced when the mouth of a bottle is blown (resonance), and when a resonator whose volume and opening area are known in advance is used, it is possible to estimate the volume of the object from the resonance frequency that changes depending on the object inside (Fig. 5.4) [7]. On the lunar farm, potatoes are also cultivated by mist, such that the potatoes grow in the underground space. The volume of potatoes can be estimated by measuring the change in the resonance frequency of the underground space at that time.



$$f = \frac{c}{2\pi}\sqrt{\frac{S}{VL}}$$

Fig. 5. 4 Schematic diagram of the Helmholtz resonance and theoretical formula of resonance frequency, c; the equation in the figure represents the speed of sound.

Sweet potatoes are usually grown from seedlings. In this case, as described above, it is necessary to secure a source of seedlings for planting in the same number each day in continuous cultivation. On the other hand, leaves are also required for the photosynthesis of potatoes, and it is not possible to supply all the leaves from the vines of potatoes during cultivation as seedlings. Additionally, sweet potato seedlings can be eaten, and this working group is also considering that they can be eaten as nutritious foodstuffs. Under these circumstances, new seedlings need to be produced by growth point culture [8], or many potatoes need to be cultivated to supply seedlings and edible leaves. Another possible countermeasure is cultivating one strain and continuing to harvest it for a long time. Because the environment can be flexibly adjusted on the lunar farm, it may be possible to continue producing sweet potatoes for 1 to 2 years once planted. Seedlings are collected from sweet potatoes during cultivation by a robot. The work of planting a part of the collected seedlings is considered to be feasible with existing mechanical technology.

5.3.4 Potato (continuous method)

Items Number	Process	Application technique	Existing/newly developed	Remarks
4.1	Planting (seed potato)	Fluorescence image analysis	New	It is possible to determine the bud
4.2	Measurement of growth status	Image analysis (visible light/multiple wavelengths)	Existing	Software may need to be developed
		Application of automated chlorophyll fluorescence measurement	Existing	
4.3	To determine the appropriate time for harvest	Helmholtz resonance and imaging judgment	New	Is the ratio occupying the space required?
4.4	Harvest (potato)	Possible if appropriate weight (volume)	New	

The continuous method is applicable for potatoes and sweet potatoes.

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5.3.5 Lettuce (continuous method)

Items Number	Process	Application technique	Existing/newly developed	Remarks
5.1	Seeding	Automated seeding	Existing	
5.2	Measurement of growth status	Image analysis (visible light/multiple wavelengths)	Existing	Software may need to be developed
5.3	To determine the appropriate time for harvest	Image analysis (leaf color, size)	New	
5.4	Harvest	Possible if appropriate weight (volume)	New	Is there a sorting method for roots of non-edible parts?

Lettuce is the most commonly produced crop in existing plant factories, and cultivation methods using multi-stage cultivation shelves have been established. In the lunar farming field, to save space, we propose a method of spreading stock intervals gradually, similar to that for sweet potatoes and potatoes, in addition to multi-stage cultivation (Fig. 5.5).

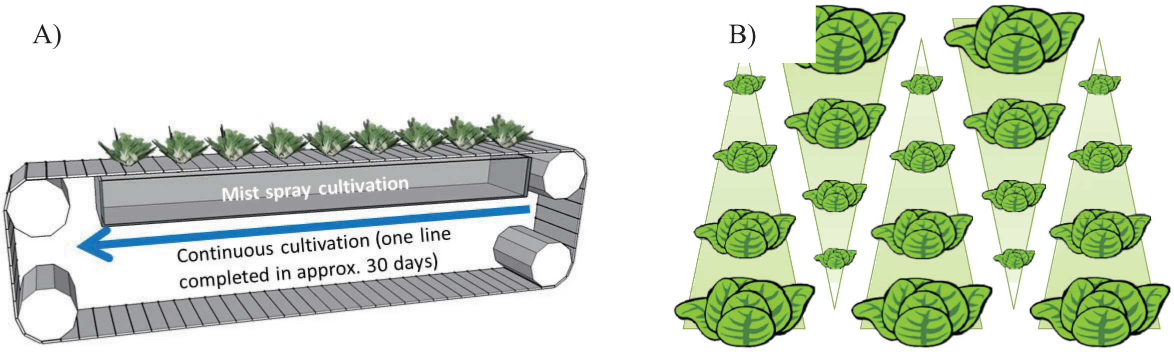

Fig. 5.5. Image of continuous cultivation method of lettuce
A) Schematic diagram of a conveyor and its interior underground for mist spray cultivation
B) Schematic diagram of growing strains and further positioning of multiple pieces of machinery in opposition

Actually, to improve space efficiency, there is a method already demonstrated in lettuce cultivation in which lettuce moves spirally from the center to the outer periphery in a circular aquarium, and the space between the plants is increased in the process. (Fig. 5.6) [9].
If the cultivation space is used reasonably and the mist containment technology can be established, it is a promising cultivation method.

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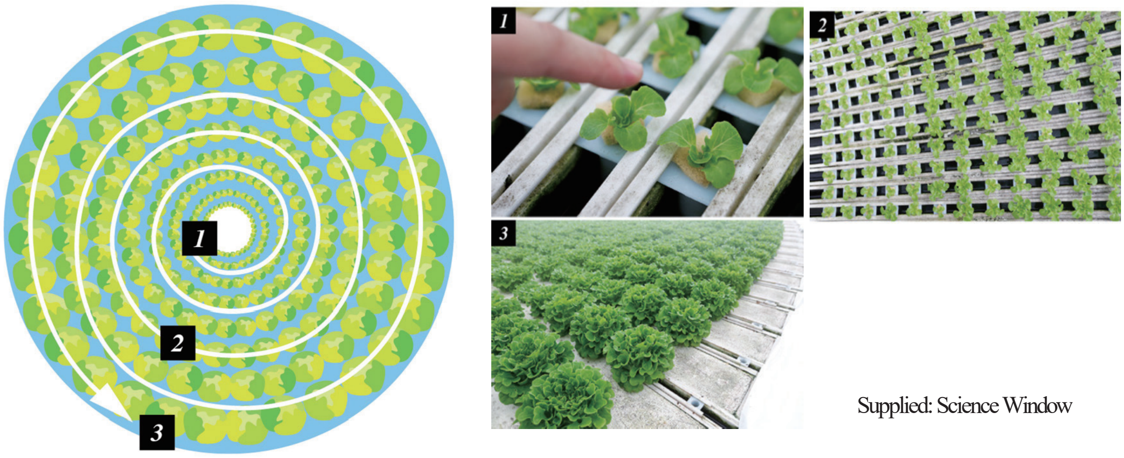

Fig. 5.6 Schematic diagram of the cultivation method that moves spirally from the center to the outer circumference and the actual inter-strain adjustment method

Numbers 1–3 in the left schematic correspond to those in the right photograph.

1, immediately after emergence; 2, gradually growing lettuce; and 3, lettuce subjected to inter-strain adjustment during inter-harvest.

5.3.6 Tomato (multiple shelves)

Items Number	Process	Application technique	Existing/newly developed	Remarks
6.1	Seeding	Automated seeding	Existing	
6.2	Seedling growth	Automatic transplanting apparatus	Existing	
6.3	Measurement of growth status	Image analysis (visible light/multiple wavelengths)	Existing	Software may need to be developed
6.4	Attraction	Examination of light direction	New	Is it attached to the shelf by bottom irradiation?
6.5	To determine the appropriate harvest time	Image analysis (fruit color, size)	New	
6.6	Harvest	Harvesting by robotic drones	New	

Seeds of tomatoes are germinated, seedlings are efficiently produced, and then planted and moved to primary cultivation. Commonly used cultivation methods include "multi-stage cultivation," in which one strain is cultivated for an extended period and the fruits that grow one after another are harvested; "low-stage-density planting" that limits the number of fruit clusters to approximately 2 to 4 per plant and increases the planting density and rotation of the plant to secure the yield; or a cultivation method that combines multiple stages and low stages are also adopted for each season [10]. We propose a multi-level shelf system at the lunar farm where shelves for growing several tomato seedlings flatly and radially are used as unit modules and stacked vertically (Fig. 5.7). Although the growth period is close to low-stage-density planting, it is an important examination item for labor-saving if the yield can be secured without performing side bud scraping or pinching. Each unit module on the cultivation shelf is circular, as shown in Fig. 5.7 A, with LED lighting and a central mist supply. After planting the seedlings in the center, it is expected that the plant will grow in a plane along the shelf surface because the LED irradiation is upward. Fruits are also thought to result on the shelves and are harvested in collaboration with a harvesting (peduncle-cutting) robot that operates on the shelves and a transport drone. Fig.

5.7 B shows the layout assumed by converting the required area when supplying 100 residents with the multi- stage device proposed. The unit modules stacked in four stages were covered with a container to form an environmental management unit.

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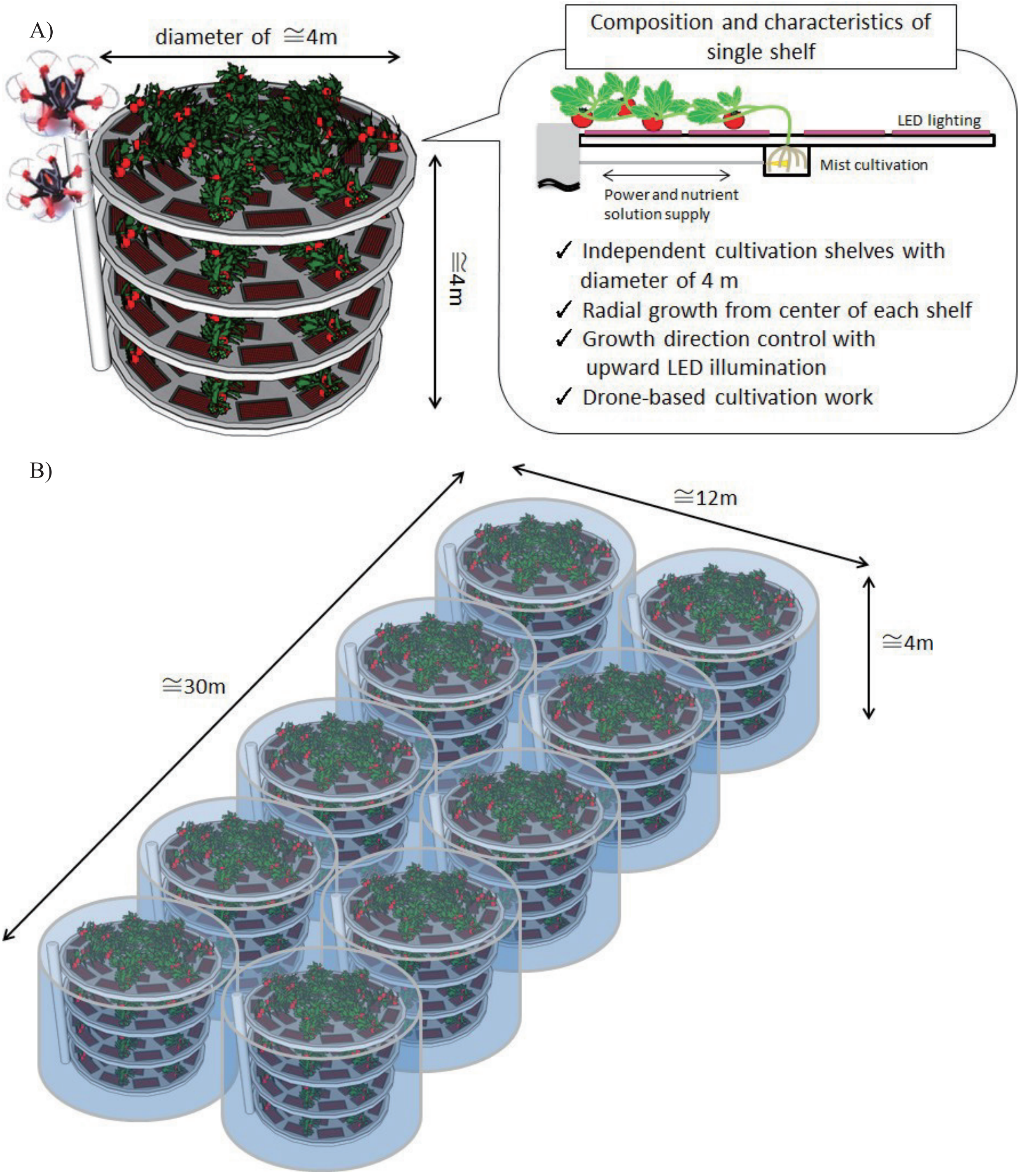

Fig. 5.7 Image of multi-level shelves for tomato cultivation
A) Image and size when the unit module is a set of four stages
B) Proposed system for supplying 100 residents

In this cultivation method, the distance between each unit module is as narrow as approximately 50 cm, such that automatic cultivation and harvesting by robots and drones is a prerequisite. Artificial intelligence (AI), which has been remarkably developing in recent years, has not yet realized the technology to accurately recognize and harvest tomatoes upon ripeness (sugar content) and size suitable for harvesting on shelves with intricate leaves and stems. The automatic harvesting method using the above image judgment method is steadily increasing. What needs to be developed in parallel with the technology for automatically "recognizing" fruits is the

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independent and collaborative control method of harvesting robots (including a peduncle-cutting robot [12] and transport drones.

5.3.7 Cucumber (multiple shelves)

Items Number	Process	Application technique	Existing/newly developed	Remarks
7.1	Seeding	Automated seeding	Existing	
7.2	Seedling growth	Automatic transplanting apparatus	Existing	
7.3	Measurement of growth status	Image analysis (visible light/multiple wavelengths)	Existing	Software may need to be developed
7.4	Attraction	Examination of light direction	New	
7.5	To determine the appropriate harvest time	Image analysis (leaf color, size)	New	
7.6	Harvest	By a robot drone	New	

The same cultivation method as tomatoes can be applied. However, both leaf and fruit colors are close to green, and it is expected that the discrimination based on the image of the fruit is more difficult than of the tomato.

5.3.8 Strawberry (individual)

Items Number	Process	Application technique	Existing/newly developed	Remarks
8.1	Planting (runner management)	Automatic aerial seedling collection using drones	New	
8.2	Flower number regulation	Image analysis	Existing	
		Cut flowers (manipulator/laser)	New	
8.3	Measurement of growth status	Image analysis (visible light/multiple wavelengths)	Existing	Software may need to be developed
8.4	Pollination	3D machine vision	New	
		Ultrasonic pollination	New	
8.5	To determine the appropriate harvest time	Image analysis (real color, size)	New	
8.6	Harvest	Harvesting by robotic drones	New	

As a strawberry cultivation method, as shown in Fig. 5.8 below, we propose a method in which seedlings are planted in multiple ridge-like cultivation devices, and the strawberry fruits hang down on the aisle side because of the shape of the ridges and are harvested. This is based on the existing technology of elevated cultivation. Planting and renewal are conducted all at once for each cultivation device. In general, it is possible to continue harvesting for 6 months, after approximately 2 to 8 months after planting, such that 10 cultivation devices are assumed to be in parallel to level the yield.

The main challenges that can be expected when growing strawberries on a lunar farm are runner management and automatic planting, automation of pollination, and the introduction of robotic drones for harvesting. Efficient production and management of runners are important because approximately 1,000 seedlings are required for a cultivation device with a cultivation area of 55 m^2 (0.5 m × 110 m) per plant.

A method called “aerial seedling collection,” which is an existing technique for collecting seedlings of runners hanging from an elevated cultivation device [12] can be adopted for runner production. This method utilizes strawberry runners that naturally generate root primordia without contact with soil, and unmanned and highly efficient planting can be achieved if the rooting site can be recognized and seedlings can be collected

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automatically by the drone.

Harvesting strawberries is conducted by using multiple drone robots in a coordinated manner. Fig. 5.8 illustrates a positioning system using sound (spectral spread sound) to control a drone robot [13]. In this example, the robot and the drone are separated, and a robot dedicated to fruit collection cuts the strawberry fruit from the stalk, and the drone collects them and turns them in. If a positioning system using sound is established for positioning individual machines, it will be possible to avoid obstacles using sound diffraction even when hidden behind cultivation equipment and plants.

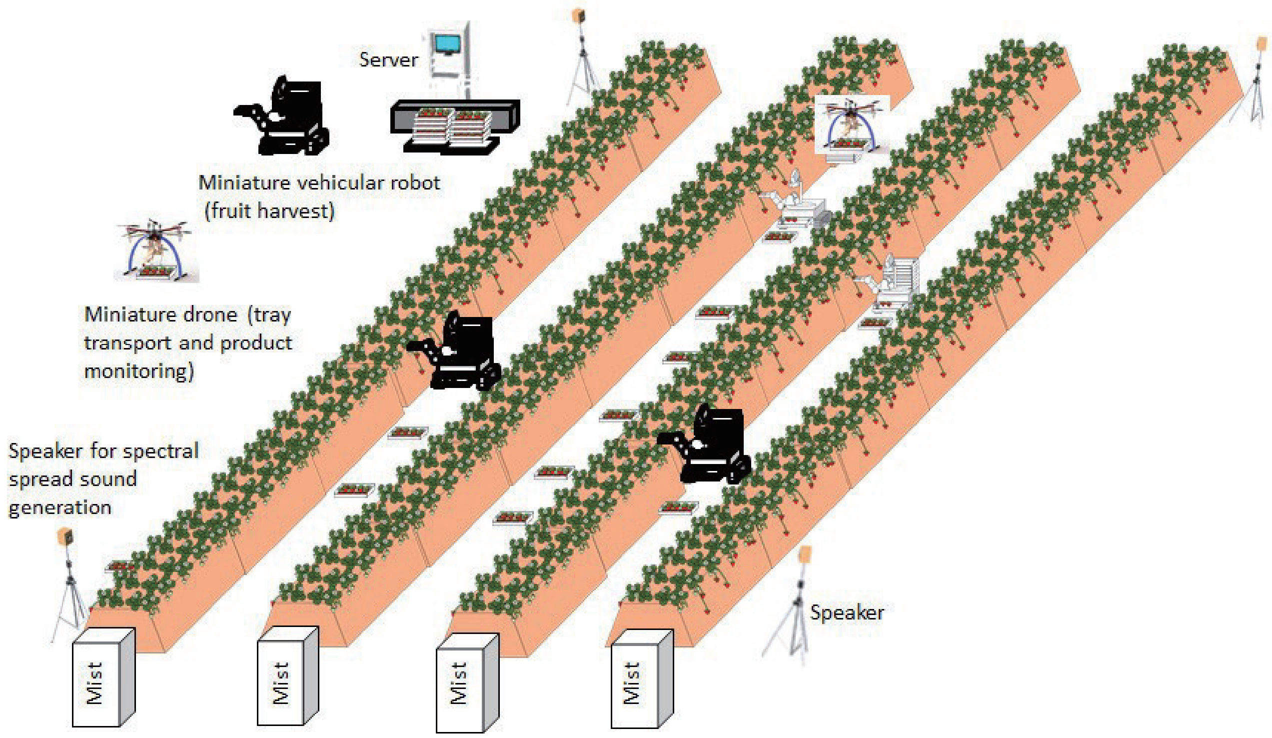

Fig. 5.8 Schematic diagram of multiple drones and harvesting robots controlled by the strawberry cultivation method and spectral diffusion sound signal

Strawberries need to be pollinated to bear fruit, and even in agricultural settings, bees are used to pollinate or manually pollinate. Because there is a high possibility that securing and maintaining individuals will be a problem when using bees on lunar farms, a technique for automatically and mechanically pollinating is desired. A promising technology is a non-contact system that combines a phased array with 3D image recognition and uses ultrasonic pulse pressure to shake and pollinate strawberry flowers [14]. Fig. 5.9 shows a schematic diagram of the appearance and operation of the system. The device runs along the strawberry population while recording using a 3D camera, and when a flower is recognized, it is pollinated by shaking the flower using a directional ultrasonic pulse.

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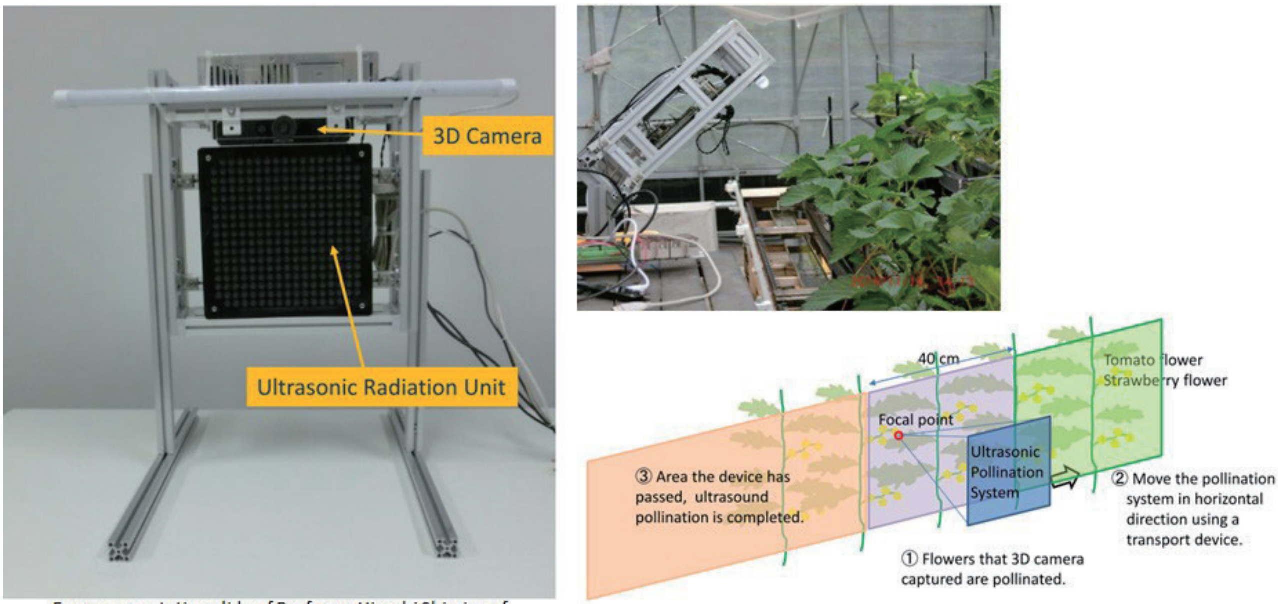

From presentation slide of Professor Hiroshi Shimizu of Kyoto University (2017)

Fig. 5.9 Strawberry non-contact pollination system using phased array and 3D camera
Left: External view of the prototype device
Upper right: The device facing the strawberry community
Lower right: Schematic diagram of the operation flow

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