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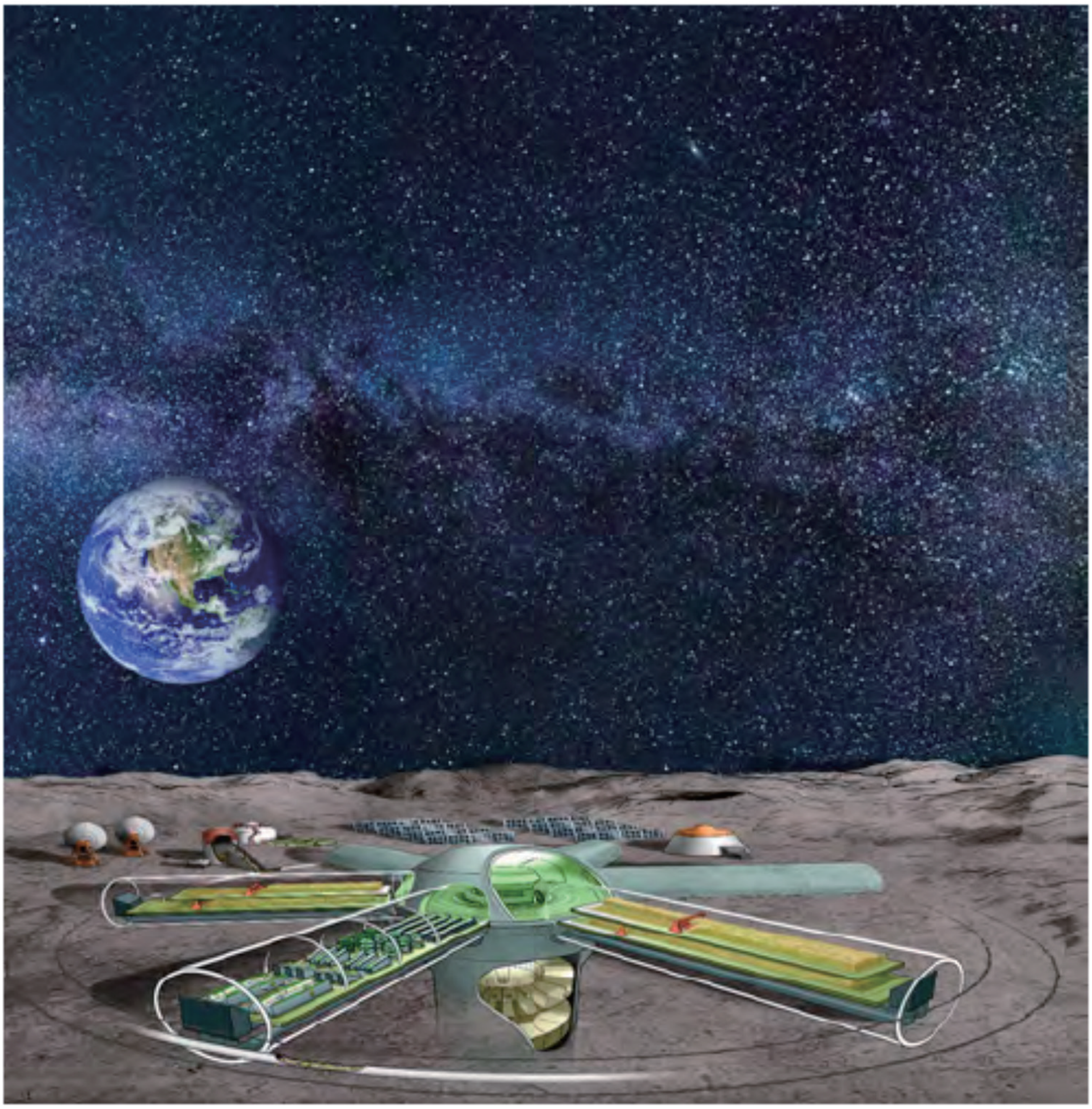
Report of Lunar Farming Concept Study Working Group 1st

Lunar Farming Concept Study Working Group



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Japan Aerospace Exploration Agency

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Lunar Farming Concept Study Working Group

ABSTRACT

JAXA space exploration innovation hub center has been studying as working group activity about the concept of the realization of "Lunar Farming" assuming plant cultivation on the moon, aiming for future food production in the outer space.

The concept study members are organized by professionals in universities and private experts who are interested in lunar farms examined the lunar plant factory concept and the members are divided into four groups of cultivation technology, unmanned technology, recycling, and overall system.

In this report, we will report the results of study for each technical field about the concept of lunar plant factory which JAXA/Japan considers.

Keywords: JAXA Publication, Lunar Farming,

1. INTRODUCTION

1.1. Motive for establishing the Lunar Farming Concept Study Working Group

Eight years have passed since the completion of the International Space Station (ISS), and since humans began living in it (establishment of the Working Group), manned space exploration activities have proceeded to the next stage. In other words, we have reached the stage to expand human residence and activity to farther astronomical objects, including the moon. On earth, human activity has expanded into new areas by first exploring, then developing, and finally settling. If you compare current space exploration activities to these steps, we can say that the low orbit around the Earth, where the ISS is located, is in the settlement stage, whereas for the next target, the moon, we are advancing from the exploration stage to the development stage. However, it is also true that development has stagnated globally at this stage for various reasons.

In order to overcome this current situation, the Japan Aerospace Exploration Agency launched the Space Exploration Innovation Hub and commenced measures through further collaboration with ground technology. To be specific, unlike conventional space development that used low orbits and static orbits, JAXA focused on the common point with the earth, that is the “presence of a surface”, to try and realize the “development” of a future base for manned explorations, as well as acquiring new technology that would bring about innovation even on Earth, and not only in space, based on keywords like “Application of excellent agricultural and biotechnology on earth and further technological innovation” and “Local production and local consumption (a self-sufficient space system to minimize supply from the earth as much as possible)”.

Expanding the living and activity areas of the human race to other astronomical objects like the moon is expected to lead to the creation of a novel space-use industry, and there is growing debate internationally about the use of resources on the moon and asteroids. In the next 10 to 20 years of space exploration, new businesses are being designed not only for conventional space agencies and related companies, but also for countries and companies that want to conduct activities on the moon. In this way, it is expected that various researchers and engineers, including private companies, will be involved, and the activities will be focused towards exploring the moon and Mars through international collaboration and competition.

This working group assumes that human beings will settle on the moon in the future, and is conducting a conceptual study of a lunar farm system that enables human beings to settle safely and sustainably. Similar examinations have been conducted in the past, but with the remarkable progress of plant factories and biotechnology since then, the conceptual study of the lunar farm where cutting-edge agriculture and biotechnology on Earth are applied is a new attempt, even from a global perspective. This working group agrees with the purpose of this establishment and aims to advance these studies properly and effectively, and has been established to gather and organize the opinions of experts who have knowledge about the concept of space, the lunar surface, or the design of plant factories on the ground.

1.2. Background

(1) Overall activity of exploration hub, starting point and aim of Lunar Farming Concept Study Working Group

In April 2015, the Independent Administrative Corporation, including the JAXA, moved to the "National Research and Development Corporation" with the aim of "Ensuring the maximum achievements of research and development to contribute to the development of the national economy and other public interests". At the same time, innovation creation centered on the National Research and Development Corporation was positioned as a national priority policy. In response to these policy developments, JAXA established the Space Exploration Innovation Hub and the Next-Generation Aviation Innovation Hub as new organizations starting on April 1, 2015, and has since been engaging in open innovation research activities.

In the Exploration Hub, by matching “the research and development needs of companies on the ground” with the technological needs that JAXA needs in space exploration from the early stages of research, we have been aiming to construct a research system that converts the results of research at JAXA to innovation on Earth, and in space, as swiftly as possible. In particular, through spin-in of ground technology to space that had not been related to space thus far and developing (spin-up) new technology in the process of applying it to space exploration, we aim to contribute not only to space, but also to innovations on Earth for society (spin-out).

Future “space exploration” is gaining momentum for the human race to venture out onto the moon and Mars, whether publicly or privately. In other words, there is a need for exploration activity technologies in space environments that require "gravity", "ground", and "substance", but these technologies are preceded by technological development "on Earth", and in particular, Japan has the world's most advanced technology. At the Exploration Hub, we focus our attention on research and development activities that match the needs of the private sector.

In the exploration for this research subject, we received many proposals for applications aimed at applying to space farms and lunar farms from companies and universities related to plant factories on the ground. However, although the study of lunar farms in JAXA was conducted about 30 years ago at the Institute of Space and Astronautical Science, in reality there have not been any further specific studies since then. For this reason, we established the Lunar Farming Concept Study Working Group (Chair: Professor Goto, Chiba University) with the help of the leader in plant factory research in Japan, with the aim of introducing state-of-the-art plant factory technology on Earth developed over the last 30 years, and once again to study the lunar farm system. Through these activities, we intend to develop research activities that will inspire innovation in plant factories on Earth as well as on lunar farms.

(2) Elemental technology for sustainable food production

Ever since the year 2000, when people began to regularly stay on the ISS, it has primarily served as a manned facility for scientific experiments with the capacity for three to six people. In order to think about food production in space, at present, a regular supply of daily necessities and food to the ISS is indispensable, but in order to expand the living area of the human race to other celestial bodies such as the moon, it is necessary to develop technology to reduce the amount of supplies required from Earth, and it is therefore essential to consider food production[1)]. There is a need to identify and solve technical issues that enable sustainable food production without relying solely on dry food and retort food-like space food that has been demonstrated so far in low Earth orbit.

For sustainable food production, we need local production and local consumption technology in space to produce and regenerate air, water, materials, etc. using lunar and planetary resources. In order to cultivate food crops, it is important to increase the efficiency of light and electric energy use, increase the crop yield per area, and establish waste treatment technology to complete substance circulation. Furthermore, in order to save precious time for astronauts, we must also consider automation of farming work. In this way, these efforts will also lead to solving future social problems, in the sense that they will aim for innovative developments in elemental technology such as environmental control technology, unmanned technology, and recycling technology.

For example, LED and multi-stage hydroponic culture are examples of space-to-ground innovations that have been realized so far. The use of LEDs has spread as an effective technology for plant factories on the ground because NASA focused on saving power and promoted their use in space[2)]. With regards to multi- stage nutrient solutions as a result of pursuing ways to increase the yield in limited cultivation area towards uses in space, the approach became a popular cultivation method in plant factories. It can be said that the technological studies that assume situations with limited resources like a lunar farm also predict the social demands of agriculture. Technologies that can be used in situations where there are resource constraints such as area, power, working hours, and other limitations like those seen in space also meet the requirements for equipment development on the ground, where there are also constraints on cultivation equipment, water, fertilizers, etc. The technology for solving problems in such restricted situations has a large impact on the solutions for social problems on the ground. It is expected that this initiative will help overcome food production and resource/labor constraints in extreme environments regardless of the current global environment.

1.3. Method of study

(1) Establishment of the Working Group and subgroups

The Lunar Farming Concept Study Working Group (hereinafter referred to as the “committee”) sought the cooperation of university and private sector experts who are highly interested in lunar farming as members, and carried out studies by dividing the experts into 4 subgroups of cultivation technology, unmanned technology, recycling, and overall system to deepen the discussion of each member's specialized area.

(2) History of discussions

The kickoff meeting was held in March 2017, and since then, Working Group Meetings were held in June, September, and December of 2017, and in April and August of 2018, respectively. Discussions were carried out in each subgroup toward each meeting, and progress reports on discussions in each subgroup were made at Working Group meetings, where discussions took place among subgroups.

1.4. System of study

(1) Table 1.1 shows the members of the Lunar Farming Concept Study Working Group.

Table 1.1 Lunar Farming Concept Study Working Group

Name	Affiliation	Specialty
Hiroyuki Ito	Associate Professor, Laboratory for Future Interdisciplinary Research of Science and Technology, Tokyo Institute of Technology	Plant cultivation systems, sensors, monitoring systems
Ryosuke Endo	Lecturer of Graduate school of Life and Environmental Sciences, Osaka Prefecture University	Energy and fertilizer recovery by methane fermentation for plant-based residues
Takayuki Ohba	Professor, Laboratory for Future Interdisciplinary Research of Science and Technology, Tokyo Institute of Technology	Plant cultivation systems, sensors, monitoring systems
Makoto Kawai	Chief Researcher, Regional Revitalization and Basic Research Group, Division of Investigative Research, JA Kyosai Research Institute	Interface with agricultural practitioners, political philosophy, local administration theory, social security theory, medical policy theory
Yoshiaki Kitaya	Professor, R&D Center for the Plant Factory, Osaka Prefecture University	Controlled ecological life support systems focusing on plant cultivation and environmental monitoring and control
Masaharu Kojima	Agricultural consultant, Shoei Co., Ltd.	Farming consultant

Naoshi Kondo	Professor, Division of Environmental Science & Technology, Graduate School of Agriculture, Kyoto University	Bio-sensing systems and instrumentation, Technologies on production, grading, and storage of agricultural products and foods
Eiji Goto (Chairperson)	Professor, Graduate School of Horticulture, Chiba University	Plant factory, plant environment engineering, facility horticulture
Masanori Shinohara	Professor, Department of Natural & Environmental Science, Faculty of Life & Environmental Sciences, Teikyo University of Science	Animal behavior science, closed ecosystem experiments in environmental science and technology research facilities
Yusuke Nakai	Senior Researcher, Kyushu Okinawa Agricultural Research Center, National Agriculture and Food Research Organization	Artificial light type plant factory, plant physiology, plant biochemistry
Akimasa Nakano (Until September 2017)	Director of Institute of Vegetable and Floriculture Science, National Agriculture and Food Research Organization	Plant cultivation, advanced facility horticulture
Koki Toyota	Professor, Graduate school of Bio-Applications and Systems engineering Tokyo University of Agriculture and Technology	Soil science (soil organisms), plant protective science
Hiroyuki Miyajima	Professor, Department of Clinical Engineering, International University of Health and Welfare	Closed environment ecosystem engineering
Sachiko Yano	Associate Senior Engineer, JEM Utilization Center, Human Spaceflight Technology Directorate , JAXA	Space experiments, plant cultivation experiments
Hiroyuki Watanabe	Professor, Department of Advanced Food Sciences, College of Agriculture, Tamagawa University	Light plant physiology, plant environment control, plant factory

(2) Structure of committee subgroup
Shown in Table 1.2.

Table 1.2 Lunar Farming Concept Study Working Group – Subgroup Structure

Subgroup	Issue	Member
(1) Environmental control (Control of light, water, and atmosphere, environmental control suited to each cultivated plant)	Environmental control of cultivation	Kitaya (Lead) Watanabe
(2) Unmanned work Maintenance of culture environment, monitoring of plants until sowing and	Sowing/growth Cultivation/harvest	Kondo (Lead) Ohba Ito

harvesting, unmanned/robot-controlled technology, etc.		
(3) Recycling Soil improvement, re-use (recycling) of limited resources, recycling of inedible parts and waste material etc.	Recycling Soil improvement	Toyota (Lead) Nakai Kojima Endo Nakano (until September 2017)
(4) Overall system Study of the system as a whole	Crop species examination System examination	Goto (Lead) Shinohara Yano Kawai Miyajima

1.5. Prerequisites and hypothesis

The studies will be advanced based on the following prerequisites and hypotheses:

(1) Approximately 1/6 of the gravity on earth (1.7 m/s^2)
(2) In the scenario of constructing the lunar surface base, we assume for the time being that 6 persons (4 to 8) will stay on the moon for the study of the lunar farm, taking into consideration unmanned, manned short-term, manned long-term, and general residence stays.
(3) To estimate the required amount of crop species by considering not only leafy vegetables such as lettuce, but also crops that can self-supply basic energy and nutrients even if the supplies from earth are delayed.
(4) We minimize the use of substances collected from lunar surface (water mined from the polar region of the moon, as well as oxygen, phosphorus, potassium etc.) and the amount of substances brought from the Earth (compensation for substances collected from lunar surface, for example, carbon dioxide, nitrogen etc.) to necessary level, estimating the necessary amount of those substances for recycling all materials.
(5) To estimate the necessary amount of electricity available from solar power generation.
(6) If LEDs will be used, the lengths of day and night should be adjustable at will, and the manner of adjustment should be examined. If sunlight will be used, consider cultivation methods inside a facility made from a new material that protects from radiation and meteorites etc., but allows the passage of visible light and infrared radiation.
(7) The atmospheric pressure and partial pressures should be adjustable to what is required.
(8) Necessary temperature adjustments should be possible.
(9) As little waste as possible should be discharged, regardless of whether it is gas, liquid, or solid, and these wastes should be recycled.

1.6. Lunar Farming Concept

- This working group carries out studies which are aimed at constructing a cultivation system for crops (lunar farms) that would supply energy and nutrients necessary for mankind to live without relying on supplies from Earth, assuming our explorative, short-term, and long-term stays on the moon and Mars.
- Based on the premise that the concept is feasible, while utilizing the cutting-edge agricultural technology and robot technology that Japan has cultivated to date, we will develop and integrate them to another level and actively use an extrapolation of technology that we assume we will have realized by the 2030s.
- The decrease in the number of agricultural practitioners in the future will bring an era that requires amateurs to be able to start farming at the same level as exemplary farmers. In view of such a future, we will find technology that uses machinery and robots, allowing for the spread of automated and unmanned operations that reduce the burden of farming work. This is very compatible with lunar farms where it is necessary to reduce the labor burden of astronauts.

- In particular, in our studies we will identify and actively incorporate technologies that will lead to further development of plant factories on earth and provide solutions to problems. Additionally, we intend for this study to be the concept of a partial demonstration test, if necessary.
- Our studies will refer to the studies and experiments performed by other countries and the Aomori Institute of Environmental Sciences in the past, and rather than simply following them, we will incorporate Japan's uniqueness as much as possible.
- We assume two scales of the lunar farm: a case assuming a small number of people (6 people) for the early stage to take place in the near future, and a case assuming a large number of people (100 people), for mankind to stay permanently. The number of people will be the basis of a proportional calculation when there are fluctuations in the number of people in both the small-number case and large-number case.
- Among the important elements for realizing the lunar farm, we will focus on saving space, energy, and resources (water, O_2, CO_2). In addition, the study will close with a module that is responsible for plant cultivation on the lunar surface base, and we will not examine other interactions with the lunar surface base, such as the residence module and experiment module. With regards to energy and resources, we will mention the IN/OUT interface closed in this module.
- This study is not for Japan (JAXA) to narrow down the way that lunar farming should be, but will instead be to describe the various ideas produced during the study, including the merits and demerits etc. We hope that this will inspire various ideas and new ideas from the readers of this study report and lead to further deepening of the study.

References

1) Sachiko Yano, Possibilities in agriculture and industry that start on the lunar surface – NISTEP predictive investigation and JAXA Lunar Farming Concept Study Working Group activity update -, STI Horizon Vol.4 No.3 26-31, 2018.
2) Raymond Wheeler, "Agriculture for Space: People and Places Paving the Way," Open Agriculture. 2017, 2, 14-32.

2. PAST AND PRESENT OF SPACE FARMING

Masanori Shinohara (Professor, Department of Natural & Environmental Science, Faculty of Life & Environmental Sciences, Teikyo University of Science)
Sachiko Yano (Associate Senior Engineer, JEM Utilization Center, Human Spaceflight Technology Directorate, JAXA)

2.1 History of space farming

Approximately 60 years have passed since the United States and the former Soviet Union began space development using artificial satellites and manned spacecraft in the 1960s. In 2018, the International Space station (ISS) celebrated its 20th anniversary of operation. Humans have been trying to extend viable areas to the vicinity of the moon, the lunar surface, and Mars. Food production is the key technology needed to make long- term manned space activities sustainable with environmental control, automation, and recycling. The Controlled Ecological Life Support System (CELSS) encompasses these techniques, and the Bioregenerative Life Support System (BLSS) utilize organisms for life support systems.

From the early stages of space development, the United States and Russia (including the former Soviet Union) have also actively addressed plant cultivation in space vessels. Plant research in space environments has been categorized into gravitational physiological research exploring gravity-sensing mechanisms and plant responses to light and gravity, space agronomic research with the goal of sustained crop production with agronomic approaches, and plant physiological research that has been mainstream in space using relatively small cultivation devices. Large-scale cultivation studies aimed at BLSSs have been conducted in laboratory facilities on earth. Terrestrial closed ecosystem cultivation facility research is being conducted by Russia, the USA, Europe, Japan, and Canada, or in cooperation. More recently, China has been actively conducting research. Fig. 2.1 shows a summary of the history of BLSS research [1].Fig. 2.1 History of bioregenerative life support system (BLSS) research

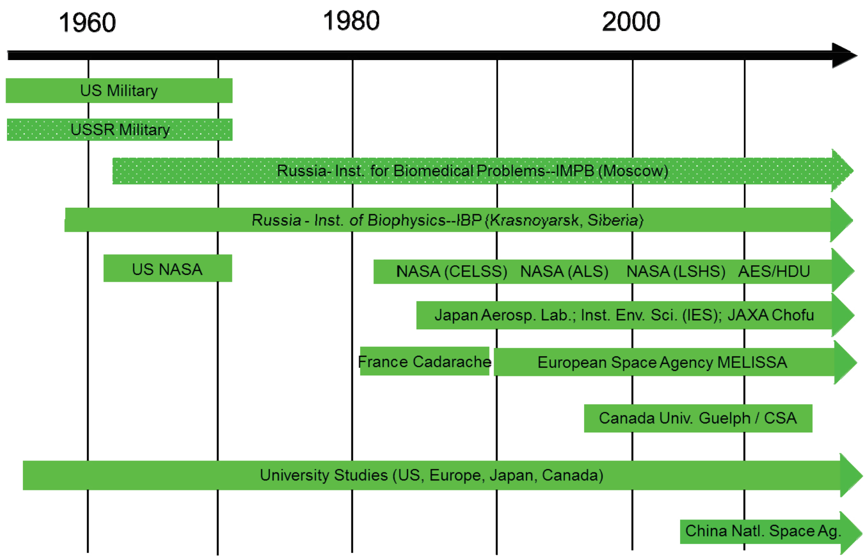

Fig. 2.1 History of bioregenerative life support system (BLSS) research [1]

2.2 Use of algae

In early life support technology research in space development from the 1950s to 1960s, research on oxygen generation and carbon dioxide removal was actively conducted using algae, such as *Chlorella*. However, the weight and electric power of the photosynthetic air regeneration system were not suitable for the short-term stay in space of the Mercury and Gemini projects, and they were not adopted. However, there is room for examination of the efficacy of utilizing algae for long-term stays, and it has been shown that it is necessary to solve problems such as edibility and the generation of volatile gases [2)].

2.3 Space farming by each country

2.3.1 Russia (including the former Soviet Union)

As a ground experiment regarding life support research in closed environments, Russia has conducted plant cultivation research for life support in closed environments using the ground facility BIOS, set up in Krasnoyarsk in Siberia since the 1950s (Fig. 2.2)[2)]. Studies on the recycling of gases, nutrients, and water were conducted using wheat and other species in BIOS. Studies utilizing plants for food production and oxygenation were conducted in phytotrons with a cultivated area of approximately 20 m^2 for more than 15 years, and algae were also studied. However, because the algae culture tank was connected to the plant cultivation area, the growth of tomatoes and potatoes ceased, the flowering of cucumbers stopped, leaves became etiolated, and an accumulation of anthocyanin was observed in the leaves of beets. Consequently, problems, such as the suspected generation of toxic volatile gas components by algae that inhibited plant cultivation became clear. Subsequently, quantitative cultivation data were obtained with a total cultivation area of 41 m^2 using two BIOS-3 phytotrons. Experiments using growing wheat in regenerated water from human urine revealed the need for sodium removal in water recycling, including sodium accumulation in culture water.

The BIOS-3 research team conducted ground experiments with the premise of developing bioregenerative technology as a large-scale closed life support system. However, the Russian Institute for Biomedical Problems (IMBP) began cultivation experiments in space, set on their manned space station and later on the ISS. Russia launched the first manned space station, Salyut, in 1971 and conducted plant experiments using the Oasis plant cultivation system[3)]. Russia has repeatedly improved the cultivation equipment with improvements in the space station and installed the SVET plant cultivation equipment in their next manned space station Mir (Fig. 2.3).

Additionally, the Russians continuously developed and used space cultivation equipment, such as the Lada plant cultivation equipment (Fig. 2.4) installed in the Russian module of the ISS. The cultivation of various plants, including wheat, barley, soybeans, and mizuna, has been attempted, and data on water and gas environments have been acquired. At the beginning of the experiments in Salyut and Mir, growth inhibition and fruiting failure were observed. It was finally concluded that it was because of the accumulation of ethylene, suggesting the necessity of gas exchange and an ethylene removal filter inside and outside the cultivation equipment. The goal of IMBP is to produce food in a microgravity environment during the period of travel to Mars by advancing research at the space station[2)].

Fig. 2.2 BIOS-3 by Russia

Fig. 2.3 Plant cultivation on the Russian Space station Mir (provided by NASA)

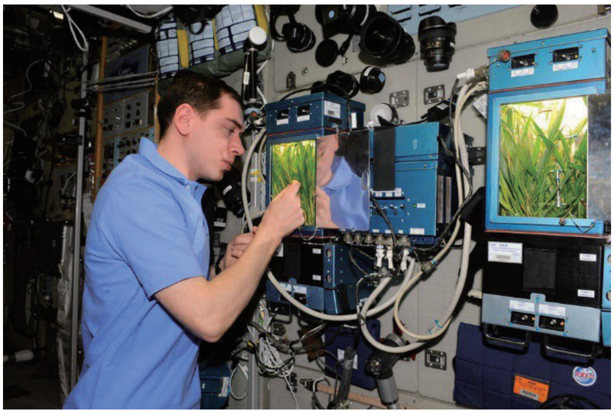

Fig. 2.4 Plant cultivation in the ISS Russia module (provided by NASA)

2.3.2 United States

(1) Overall

In 1958, just before NASA was launched, the Biologistics Symposium was held in Ohio to create a list of crops that would be needed to support people in space[2]. The criteria of growing even at low-light levels, with compact size, high yield, and resistance to salt (sodium), which is a problem in recycled urine, were organized and 13 types of crops, such as sweet potatoes, lettuce, Chinese cabbage, cabbage, turnips, and cauliflower were selected. In the 1960s and 1970s, the U.S. military was also heavily involved in the space program, and plant research for life support was conducted. Then, high-light output by artificial light became technically possible because of technological advances over the previous several decades, and research progressed to design cultivation spaces such as vertical farming, hydroponics, and attempts to increase photosynthetic efficiency through high CO_2 cultivation[4].

In the 1980s, NASA re-engaged in CELSS research and discussed crop cultivation during workshops. At NASA, plant-related studies were conducted in three laboratories: the Kennedy Space Center (KSC), Lyndon B. Johnson Space Center (JSC), and Ames Research Center (ARC). NASA also granted research funds to universities[5]. As a result, wheat, rice, potatoes, sweet potatoes, soybeans, peanuts, and lettuce were selected as crops cultivated in CELSS. A study was conducted in which NASA and the university shared data on cultivation methods, growth measurements, and gas exchange. In addition to KSC, Purdue University, Utah State University, University of Wisconsin, and Tuskegee University conducted the experiments (Fig. 2.5)[1]. At the Advanced Life Support Plant/Food Production Meeting in 1997, 23 crop species were proposed in recognition of the nutritional aspects necessary for life support, crop yield index, ease of cooking, and cultivation performance in a closed environment[6]. The use of LED light sources in space and vertical/multi-stage farming were technological innovations, and space use research became a useful example of terrestrial agriculture.

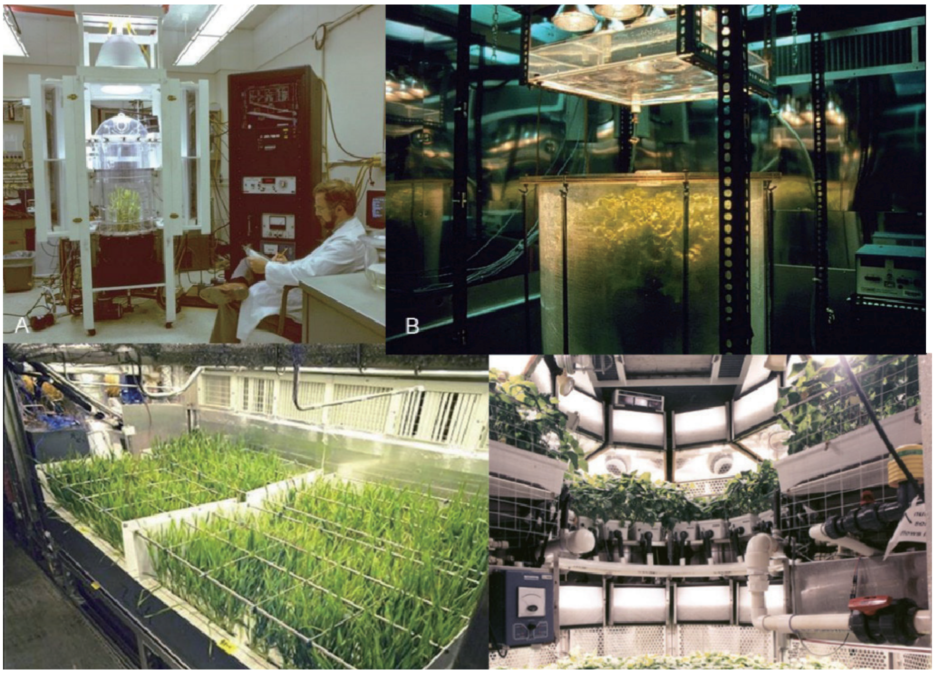

Fig. 2.5 Previous closed ecological test facilities at NASA[1]
A) Ames Research Center Closed Chamber System, B) Purdue University Minitrons,
C) Johnson Space Center Variable Pressure Growth Chamber,
D) Kennedy Space Center Biomass Production Chamber

(2) NASA bio-regeneration type on-ground tests

Similar to the Russian BIOS project, research by NASA also took into account the application for use in space stations and on planets, and research is being conducted to control the environment, such as water supply and drainage, with the premise that there will be gravity. Ground-based studies have been extensive for closed ecosystem life support systems, especially for bioregenerative studies involving plant cultivation, because of their considerable size. Ground-based experiments funded by NASA have been extensively studied in small-scale growth chambers with cultivated areas ranging from 1 to 4 m^2. Additionally, the Biomass Production Chamber (BPC), operated at KSC from 1988 to 2000, is well known as a large-scale experimental facility (Fig. 2.5D). BPC has 20 m^2 of cultivation area, and a vegetation cultivation study was conducted for life support in space in a closed system. The BPC utilized NFT-hydroponic cultivation, with four shelves placed in a 7.5 m high chamber. Here, wheat cultivation was conducted for 86 d, potatoes for 105 d, soybeans for 90 d, lettuce for 28 d, tomatoes for 85 d, as well as rice and radish cultivation. Data on yield changes due to carbon dioxide concentration and ethylene accumulation were collected [2].

In particular, NASA had a Lunar Mars Life Support Project (LMLSTP), an example of simultaneous food production and residence at a ground experiment facility. LMLSTP was a project conducted at NASA JSC from 1995 to 1998[7]. It was conducted in a four-stage closure experiment. Phase I was an experiment involving one person for 15 d, while phase III was an experiment involving four people over 91 d. In particular, in Phase III, air and water were implemented as a completely closed system, and food and waste treatment were implemented as a partially closed system (Table 2.1)[8].

Table 2.1 Lunar Mars Life Support Project (LMLSTP) [8)]

Test	Phase I	Phase II	Phase IIA	Phase III
Duration	15 days	30 days	60 days	91 days
Crew	1	4	4	4
Types of Systems	Biological (Wheat)	Physicochemical (Advanced)	Physicochemical (ISS Regenerative ECLSS)	Integrated Physicochemical & Biological (Advanced)
Full Closure	Air	Air & Water	Air & Water	Air & Water
Partial Closure				Food & Waste
Open Loop	Water, Food & Waste	Food & Waste	Food & Waste	

NASA also built BIO-Plex (Bioregenerative Planetary Life Support Systems Test Complex) at JSC. BIO-Plex was equipped with two large agricultural modules (Biomass Production System), each 80 m^2 [9)]; however, the plan was canceled in the 2000s. The reason for the cancellation was to concentrate funds on NASA's constellation plan, and a full-scale experiment as a closed life support system with biological regeneration was terminated at a stage where only the structure (Fig. 2.6)[10)] was completed because of policy changes caused in part by a lack of planned funds. The Obama administration also canceled the constellation plan in 2010.

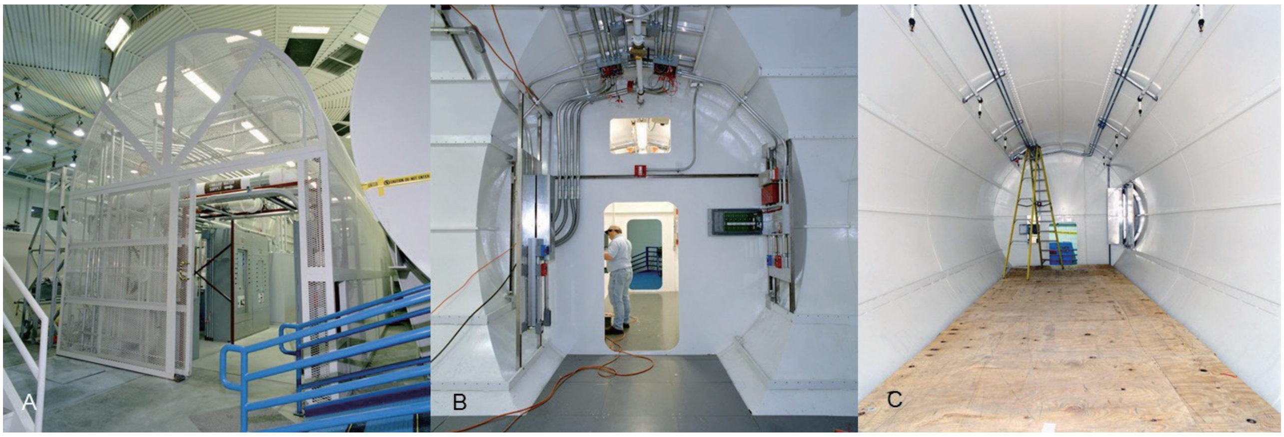

Fig. 2. 6 Bioregenerative Life Support Systems Test Complex (BIO-Plex) [10)]
Constructed as a large manned facility for four people living within for 1 year and constructed at the NASA Johnson Space Center.
A) View of exterior, B) View of interior, C)View of interior

(3) Space experiment

NASA has been developing cultivation element technology that can function even in a microgravity environment simultaneously with the CELSS research assuming a planet where gravity exists. Many studies have been conducted on water supply systems that are easily affected by gravity and photosynthetic efficiency because of the light environment. NASA provided research funds to universities and others to research water supply systems that use porous tubes and membranes. These achievements led to the system design of a salad machine that provides astronauts with fresh vegetables. Although the size of the experiment was small, the plant cultivation equipment Astroculture (ASC) and Advanced Astroculture (ADVASC) were installed on the Space Shuttle and ISS from the 1990s to the 2000s, and cultivation experiments were conducted. Later, plant cultivation equipment, such as the Plant Generic Bioprocessing Apparatus (PGBA), Biomass Production System (BPS), and more recently Veggie (Fig. 2.7), were developed by NASA and NASA-funded research. Most were used in gravitational biological studies and were small experiments for food supplies.

In an example of an experiment that focused on space agriculture using space equipment, Russia and NASA jointly grew wheat in the plant cultivation equipment SVET on the space station Mir[11)], potatoes in ASC[12)], and wheat in BPS[13)] measuring photosynthetic efficiency. The Veggie, which has been installed on the ISS since 2014, has a simple design with an LED light source, a fan that moves the air, and a water supply system operated by the crew. It has also been used in plant physiology experiments and experiments on the cultivation of lettuce and other plants. Bacterial examinations were also conducted with an awareness of HACCP in space, and the cultivated samples were frozen and examined on earth, followed by the first formal astronaut-eating event of lettuce cultivated in August 2015, the second time it was cultivated (Fig. 2.7C). Next, Zinnias were harvested in 2016, and Tokyo Bekana was harvested in 2017. Tomato cultivation was planned for 2018[14)]. Additionally, the United States launched the Advanced Plant Habitat (APH) on the ISS in 2017 and installed it in the Japanese Experiment Module "Kibo" to conduct the first cultivation experiment (Fig. 2.8).

Fig. 2.7 ISS NASA cultivation equipment Veggie (provided by NASA and Food Production for Space Exploration[14)])
A) Veggie appearance (photographed on earth), B) Astronaut Steve Swanson harvesting lettuce on the ISS (June 2014), C) Astronauts Kjell Lingren, Scott Kelly, and Kimiya Yui growing lettuce on the ISS, (August 2015) and D) Zinnias blooming on the ISS (February 2016)

Fig. 2. 8 NASA Plant Cultivation Device "Advanced Plant Habitat" (APH)
A) Wheat growing inside APH, B) Science Carrier removed from APH with wheat, and C) Astronaut Norishige Kanai removing the Science Carrier where the wheat grew from APH (provided by NASA)

(4) Non-NASA space farming-like terrestrial experiment equipment, "Biosphere 2"

Biosphere 2 is a large privately sponsored closed environmental facility built in Oracle, Arizona, from the 1980s to the early 1990s. It was planned that 2,720 m^3 of soil would be brought into the vast 2,000 m^2 agricultural area to provide 80% of the food for eight people to live for 2 years. In a complex system containing a wide variety of plants and animals, the goal was to challenge life support and biological regeneration techniques in a closed environment with a view for space applications. The closure experiment was conducted twice for 2 years from 1991 to 1993 and for the following 6 months; however, the first 2-year test failed to maintain a completely closed environment, and in the 16th month, the oxygen concentration became 14%, and the closed system was forced to open. Insects and birds also died because of fluctuations in carbon dioxide concentrations[15)], and there were also food shortages. Changes in the gas environment speculated to have been caused by a lack of sunshine and soil bacteria respiring beyond expectations[16)]. In addition to these factors, it has been noted that there were psychological problems between the crew and operation staff.

(5) Mars Simulation Experimental Facility MDRS

The Mars Desert Research Station (MDRS) is a Mars simulation facility owned by the Mars Society, a U.S. nonprofit organization in Utah, the United States. Approximately six teams stayed for 2–3 weeks and experimented with simulating residence on Mars. From Japan, Mars Society Japan dispatched eight participants in 2014 and 2015. A food-producing and plant-science laboratory called GreenHab has also been established to study the type and quantity of food required for future Mars manned missions. Recently, Yusuke Murakami of the Mars Society Japan participated in a long-stay mission with a total stay of 160 d in both Utah and the Arctic.

2.3.3 Europe

The European Space Agency (ESA) has been conducting a biological environment maintenance research project, including material circulation, since 1987, known as the Micro-Ecological Life Support System Alternative (MELiSSA) project. The early MELiSSA project was a waste treatment concept using microorganisms and cyanobacteria for biomass production; however, it is now expanding to including plant cultivation. MELiSSA also involves crop monitoring by remote sensing and has acquired data on the cultivation conditions of plants, such as wheat, beets, and soybeans, in a closed hydroponic environment[2)].

ESA has developed the European Modular Cultivation System (EMCS), a cultivation device for space, and it has been using it on the ISS since 2006 for plant research in space[19)]. Additionally, the German Aerospace Center (DLR) has led the development and operation of the EDEN ISS in Antarctica to research crop cultivation that will serve as food for the manned exploration era (Fig. 2.9). The EDEN ISS also has significance as a spin-off of space utilization[20)]. It is a multi-stage cultivation module for supplying fresh vegetables in the polar regions and is the only one with space utilization. The EDEN ISS container was shipped to Antarctica in 2018, operates 400 m from the German Antarctic base Neumayer-Station III, and is currently conducting cultivation experiments[21)].

Fig. 2. 9 ESA EDEN ISS plant cultivation container
A) Cultivation shelves in EDEN ISS containers,
B) Tomatoes, C) Cucumbers, D) Basil, and E) Radish grown in EDEN ISS,
F) Operation control room in Bremen,
G) EDEN ISS appearance set up in Antarctica and transport boxes with harvested vegetables carried by sled to the Neumayer Station III
Source: Facebook, @spaceedeniss

2.3.4 Japan

(1) Japanese CELSS study

The study of space agriculture in Japan is aimed at application on Mars as a destination for manned activities and was began approximately 30 years ago by Prof. Masamichi Yamashita. Activities at ISAS and the "Space Agriculture Salon" included the cultivation of highly salt-tolerant plants, honeybee flight under low gravity, and examination of menus using insect foods, such as silk moths.

However, as in CELSS research, the National Aerospace Laboratory of Japan (NAL) has been developing bioregeneration technology for closed ecosystem life support systems since the latter half of the 1980s. The

Closed Ecology Experimental Facilities (CEEF) were constructed as a facility where two people could live for 120 d in a completely closed environment with plant cultivation[22]. Built between 1994 and 1999 at the Institute for Environmental Science and Technology in Rokkasho Village, Aomori Prefecture, this facility was created to simulate radioactive nuclear dynamics in the ecosystem. This was the experimental facility that Keiji Nitta of the same institute had fostered since the NAL era. It was a regeneration device that extracted C and O_2 from CO_2 via hydrogen using a wet oxidation device that decomposed under high temperature, high pressure, and a Sabatier reaction. It was an advanced Environmental Control and Life Support System (ECLSS) incorporating elemental technologies leading to manned space development [23]. Notably, a small goat (Shiba goat) was introduced as a part of the waste treatment (ingesting the inedible parts of the plants and contributing to weight reduction and decomposition). Near the facility's completion, four researchers were selected and hired as candidates for residence since 2000 and have completed training in plant cultivation, equipment calibration, safety, and health management. In 2005, three 1-week living experiments were conducted, in 2006, 1-week living experiments were conducted six times, and in 2007, 2-week living experiments were conducted three times, followed by 4- week living experiments, after which the closed residence experiment was completed. All plant cultivation was conducted using hydroponics without soil. Rice was cultivated as a carbohydrate source in a 60 m^2 area, soybeans as a protein source in a 30 m^2 area, peanuts as a fat source in a 30 m^2 area, and 20 types of vegetables in a 30 m^2 area in anticipation of the need for other vitamins and minerals [22] [24]. In this experiment, the self-sufficiency rate was high (up to 95% for residents, 100% for goats). In addition to the practice of processing and feeding crops harvested in a closed system, Russia and NASA have been researching bacterial flora, monitoring the psychological state of residents, and organizing troubleshooting techniques unique to closed systems. The results were rigorously evaluated, even compared with the previous experiments [24].

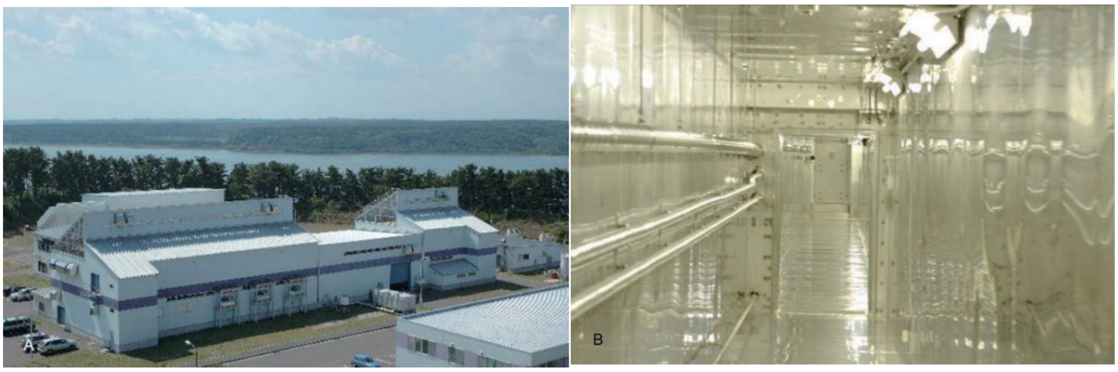

Fig. 2.10 Appearance and Interior of the Closed Ecosystem Experimental Facilities (CEEF) within the Institute for Environmental Sciences (IES)
A) CEEF and its support facilities were built inside a common building, B) CEEF constructed a highly airtight closed environment with stainless steel and glass without any concrete, and all crops were cultivated using hydroponics [22]

Fig. 2.11 Crops and Vegetables cultivated in CEEF [22) 24)]
A) Sequentially grown rice, B) soybeans, C) tomatoes D) cabbage, E) and sequentially grown crowndaisies, F) carrots, and G) vegetables

(2) Space experiment

Plant growth experiments in the dark for several days in space have been conducted on the Space Shuttle and the International Space Station. The results showed that, in addition to the lack of gravitropism in the microgravity environment, the constituents of the plants' cell walls changed, and the water tropism of the roots was more likely to appear. Regarding the Seed-to-Seed experiment, if the results of experiments in Russia, the United States, Europe, Japan, and other countries worldwide were combined, we can see that it is possible to complete the life cycle of plants and the growing environment can be adjusted, even in space. Japan has also succeeded in the Seed-to-Seed experiment (Space Seed experiment, Fig. 2.12) of *Arabidopsis thaliana* using the plant experiment unit (PEU) in the cell culture device on the ISS Japanese Experiment Module "Kibo"[25)].

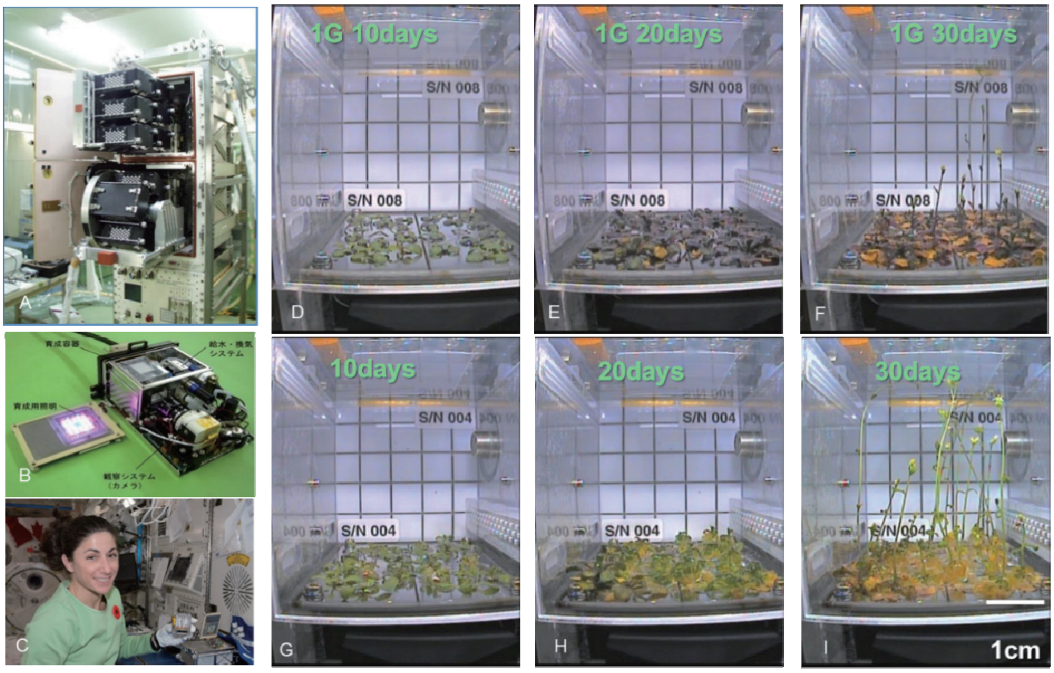

Fig. 2.12 Japanese ISS-plant cultivation experiment (Space Seed)

A) Cell Biology Experiment Facility（CBEF） is used cell culture and plant cultivation hardware in the ISS Japanese Experiment Module “Kibo”,

B) Plant experiment unit used in the cell culture device, C) NASA astronaut Nicole Stott conducting *Arabidopsis* cultivation experiments, D–F) *Arabidopsis thaliana* in PEU installed in the artificial gravity part of CBEF, and G–I) *Arabidopsis thaliana* in PEU installed in the microgravity portion of CBEF (provided by JAXA)

(3) Ground experiment

Because constant gravity exists on the planet's surface, it is speculated that problems specific to microgravity will not be applicable for cultivation on the planet surface. However, a microgravity environment was present while moving to a station near the moon (deep space gateway[26]) and planets, including Mars. During ground research focused on space plant cultivation conducted in Japan, research teams from five universities (Tohoku University, Tokyo University, Osaka Prefecture University, Utsunomiya University, and Tokai University) conducted cultivation experiments, including plant cultivation box design, ground product production, and aircraft experiments, such as "research on the life cycle of plants under microgravity and development of microgravitational field plant experiment equipment for that purpose." This research clarified that the design and verification of the lighting system, air conditioning system, airflow control, and nutrient water supply system, which are not easily affected by gravity, were important issues among the elemental technologies to realize plant cultivation in space[27]. Based on these achievements, the research progressed to technical element extraction work in the Lunar Farm Working Group of the Space Exploration Innovation Hub.

(4) Expert Committee on the Science of the Use of the Space Environment

One of the academic community support activities led by ISAS is the Space Environment Use Scientific Expert Committee. Since 2017, this expert committee has positioned plant cultivation research at the forefront of research and has provided support.

(5) Research on Elemental Technologies for Crop Culturing to Secure Stable Food during Manned Planetary Exploration

In 2015, research on elemental technologies for crop cultivation to secure stable food during manned planetary exploration was noted as technological development necessary for manned planetary exploration, and research at the JAXA Tsukuba Space Center began. They conducted research to cultivate crops to secure food for planetary bases, provide fresh vegetables for astronauts en route to the planet, and cultivate plants that contribute to mental health support. Utilizing existing plant factory technology, a system was created to collaborate with research institutes, such as universities and industries with research experience. This activity is being conducted simultaneously with the Lunar Farm Working Group activity of the Space Exploration Innovation Hub, and members of the Lunar Farm Working Group are participating in activities such as in the Advisory Committee.

2.3.5 China

Lunar palace-1 is a 160 m^2 (500 m^3) enclosed residential experimental facility for four people built at Beihang University in Beijing, China. In the 105 d closed-living experiment from 2013 to 2014, a closed-living experiment was conducted with three people and the plant cultivation module half-operated [100 m^2 (300 m^3)], and the productivity of 1.6 people was confirmed. At the time of this experiment, wheat was cultivated in 30 m^2, tiger nuts (Chufa) in 10 m^2, soybeans in 5.6 m^2, and eight species, such as leafy vegetables and strawberries in 12.7 m^2. The cultivation shelves were multi-stage with red and blue LEDs. One of the unique points was that animal breeding was not conducted, mealworms were bred for the treatment of non-edible parts and food, and feeding during the life of the actual experiment was also conducted (Fig. 2.13) [28]. From 2017 to 2018, the system was operated continuously for 370 d, two teams of four people with different metabolic rates alternately lived within 110, 200, and 60 d, and the reports indicated that the experiment was completed [29]. Researchers at Peking University have made most academic reports concerning the 105 d experiment in 2014. Academic reports have been made in various fields, including space development, ecological engineering, agriculture/plant physiology, and flora. Closed circulation has not been completed in the previous reports, and the details regarding waste treatment have not been clarified. Treatment by microorganisms was assumed, and the report of the results of this 370 d experiment is awaited.

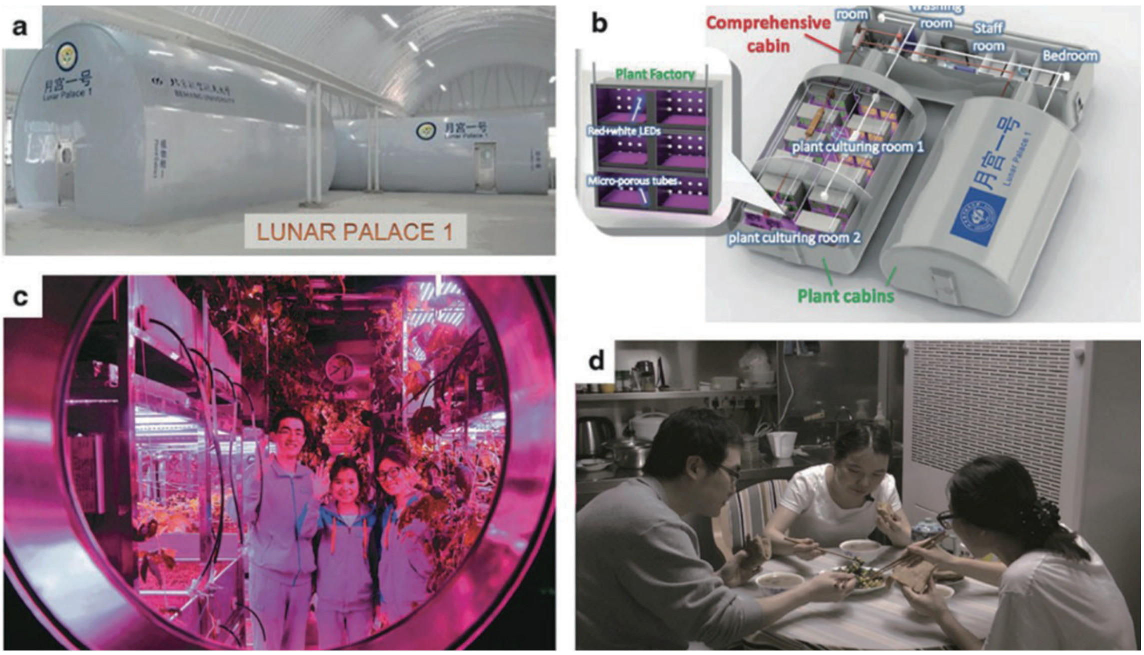

Fig. 2.13 Lunar Palace-1 [28]

Lunar Palace-1 a) Appearance, b) Illustration of the internal appearance, c) Three crew members during the 105 d experiment, and d) Mealtime during experiments

2.3.6 Others

NASA has collaborated with researchers at the University of Arizona's School of Agriculture to develop a prototype of an inflatable greenhouse for farming in space, according to information from May 5, 2017 [30]. Additionally, Russia reported a proposal for a device based on a unique idea, a six-sided cultivation device premised on space use [31].

2.4 Plant physiology in low-gravity environments

Plants acquire a mechanism that accepts and responds to the surrounding environmental stimuli; in particular, they manage their life cycle while utilizing gravity [33]. Previous studies on plant growth in the space environment have revealed characteristics, such as changes in plant cell wall constituents and the tendency for root water tropism to appear. It is also known that it is possible to complete the plant life cycle by adjusting the growth environment [27]. However, changes in plant physiology and cultivation conditions under microgravity and gravity environments have attracted attention, and there is no record of long-term cultivation under low gravity because of restrictions in the cultivation equipment and centrifuges.

Regarding the alternation of generations of plants in space, there was a problem forming fertile seeds in the space station in the early stages of space development. However, it has been found that plants can form seeds, even in the space environment, by control of the environmental factors affected by microgravity. However, abnormalities in plant aging and the fertility and shape of seeds have been observed in space, and they differ depending on the plant species.

Various plant growth phenomena affected by the gravitational response, such as water tropism, phototropism, apical dominance, and rotational turning movement, have been found in plants. Among them, research is progressing on the anti-gravity reaction, which is the reaction that conditions the body against gravity, and the direct bearer of this reaction is the cell wall. Plants use more than 90% of their fixed energy to build sturdy cell walls, and when low gravity reduces the need for anti-gravity reactions, plants will divert that energy to other needs [33]. It is interesting to observe the plant physiology that occurs when growing crops on the moon.

According to Kiss et al.[34], the results of an experiment on phototropism (TOROPI-2) using *Arabidopsis thaliana*, which is widely used in plant research as a model for higher plants, indicated that the phototropism threshold for red and blue light is approximately 0.1 to 0.3 G. In low-gravity experiments using algae, the intracellular statoliths (amyloplasts) play a role regarding weights that settle at approximately 0.1 G to 0.2 G, depending on the direction of gravity. Consequently, it can be assumed that the low gravity of the Moon and Mars is closer to 1 G, which is the same as on the ground, rather than the microgravity environment for plants.

However, low gravity may affect the cultivation equipment and environment. From the results of a short-term microgravity experiment using aircraft flights, convection disappeared because of the absence of gravity, and the temperature increase may lead to a decrease in fruit set by suppressing the heat exchange between the plant and the surrounding environment [35]. Additionally, according to a recent short-term gravity fluctuation experiment using aircraft flights, in which the gravity condition was partially changed to a gravity of 1 G or less, it was suggested that low gravity might have a considerable effect on the water distribution in the medium and the environmental control of the cultivation system [36]. It is preferable to partially verify the effect of low gravity on the cultivation system.

2.5 Results of plant cultivation in the International Space Station

(1) Purpose of Cultivation Experiments in Space

Thus far, various plants have been tested on the Space Shuttle and ISS. Besides being a food source, plants are effective for manned space activities for environmental control in a closed environment because of carbon dioxide fixation by photosynthesis and absorption/evaporation of water. Therefore, many basic experiments and cultivation experiments have been conducted to confirm growth in space, gravity, light response, and root tropism[37].

(2) Actual ISS experiments

Regardless of the shuttle era, the ISS has enabled continuous cultivation for an extended time. Equipment is also being developed by NASA, ESA, JAXA, and Russia and for joint missions. Approximately 80 plant experiments have been conducted on the ISS to date, and approximately half of them are experiments using the model plant *Arabidopsis thaliana*. Additionally, wheat, barley, soybeans, mizuna, tomatoes, radishes, and peas are cultivated on the ISS. There are also plans to grow bok choy, kale, and wasabi. There have been experimental examples using corn, cucumbers, rice, and lentils, but this experiment analyzed seedlings and roots and germination in the dark. Experiments have also been conducted using the legume Burr medic, the grass model plant *Brachypodium distachyon*, the spruce genus *Picea* (Pinaceae family), and *Quercus glauca*, poison ivy, and morning glory. Culture experiments with algae, such as *Chlorella* and *Chlamydomonas,* are also being conducted. Experiments have also been conducted on soils and plants such as rhizobia, *Bacillus subtilis,* staphylococci, and microorganisms closely related to health management.

Lettuce was cultivated multiple times from 2014 to 2015 by the NASA device Veggie. The first and second cultivations were frozen and recovered on the ground, and after analysis and microbiological inspection, they were provided to astronauts in orbit during the 2015 cultivation, and three astronauts, including astronaut Yui tasted them (Fig. 2.7).

In 2017, the NASA-developed Advanced Plant Habitat (APH) was installed in the Kibo inboard laboratory rack. APH has a cultivation area of 0.2 m^2, the largest space plant device to date, and *Arabidopsis thaliana* and wheat were cultivated for the initial verification in 2018. Fruiting of wheat has occurred (Fig. 2.8).

i) Potato cultivation

NASA is aware of the usefulness of potatoes in food production, and cultivation experiments on the Martian regolith stimulant and desert soil are being conducted in terrestrial laboratories. In space, a potato (Seed Potato) cultivation experiment was conducted in the 1995 Space Shuttle Mission STS-73, and a mid-deck rocker type cultivation device cultivated tuberous roots. The astroculture was analyzed on the ground [12)]. It was determined that there was no difference in tuberous root growth and starch particle size with that of the ground control group [38)]. In this experiment, the flight was approximately 2 weeks; thus, the plants grown on the ground for 7 weeks were loaded. There was no example of germination or harvest from seed potatoes.

ii) Strawberry cultivation

Ground studies with the goal of space cultivation of strawberries have also been attempted by NASA and ESA (EDEN ISS), but there is no space cultivation record. There are problems regarding the transportation of seedlings, the length of the cultivation period, and pollination.

iii) Cultivation of wheat, barley, and soybeans

Much has been achieved using the NASA space cultivation equipment and Russian cultivation equipment for wheat, barley, and soybeans.

iv) Tomato cultivation

Tomatoes are described as a sample in the cultivation experiment using the Lada device installed in the Russian module, but there is no record of this in literature. Tomatoes were also planned to be grown using Veggie to test light quality and fertilizer [14)]. Long-term storage of seeds before the experiment was an issue, and the effect of pollen on astronauts was considered.

v) Cultivation of lettuce and Mizuna

There have been many achievements using NASA and Russian cultivation equipment for lettuce and Mizuna.

vi) Cultivation of sweet potato

There is no information on the cultivation of sweet potatoes, although its usefulness as a target for food production in space has been recognized [6) 39)].

vii) Cultivation in educational missions

Under the application conditions of space experiments where the amount of transportation and experimental space are limited, plants can be easily stored as seed samples, a large number of samples can be transported.

Seeds are relatively easy to control as biological experiment samples because experiments can be started using the water supply, and the influence of gravity on morphology can be easily observed. Therefore, many are cultivated in missions to demonstrate their cultivation and educate children and students. In 1994, Chiaki Mukai brought Kaiware daikon(Radish Sprout) to his first Space Shuttle flight and sprouted it in his cabin. Astronaut Donald Pettit of NASA used a Ziploc bag to grow zucchini without using any special equipment and published a record of flowering and fruiting with photos and explanations. Some astronauts raised sunflowers.

At the "Space Seed for Asian Future 2013" conducted by JAXA in 2013, an azuki bean germination experiment was conducted at ISS Kibo. Additionally, educational missions using peas and barley were being conducted using the Russian cultivation equipment Lada. The European Space Agency (ESA) was also conducting experiments using arugula in educational kits.

Viii) Other

Cultured Korean ginseng cells (Zhenshen, Ginseng) have been cultured in the Russian module of the ISS from 2007 to 2009. In 2016, lettuce was cultivated during an approximately 30 d manpower experiment in Tiangong-2, a space laboratory docked with Shenzhou-11, a Chinese manned spacecraft.

Citations

1) M. Porterfield, NASA Bioregenerative Life Support: Past, Present & Future, ISLSWG Bioregenerative Life Support Workshop, Italy: http://www.asi.it/en/node/32451, 2015.
2) R. Wheeler, "Agriculture for Space: People and Places Paving the Way," Open Agriculture 2, 14-32, 2017.
3) P. Zabel, M. Bamsey, B. Schubert, M. Tajmar, "Review and analysis of over 40 years of space plant growth systems," Life Sciences in Space Research 10, 1-16, 2016.
4) E. Goto, "Construction and related experiments of a closed ecosystem life support system centered on plants," Japan Space Utilization Promotion Center, 2003.
5) E. Goto, "The Current Research on Plant Production in a CELSS in U.S.A.," Environmental Control in Biology 33(2) 89-95, 1995.
6) R. Wheeler, "NASA TM 2009-214768 Roadmaps and Strategies for Crop Research for Bio regenerative Life Support System," 2009.
7) N. J. Packham, "The Lunar-Mars Life Support Test Project: the Crew Perspective," https://lsda.jsc.nasa.gov/books/ground/1.3Crewmembers.pdf.
8) D. J. Barta, The Lunar Mars Life Support Test Project, JSC-CN-36382, 2016.
9) D. J. Barta, J. M. Castillo, R. E. Fortson, "The Biomass Production System for the Bioregenerative Planetary Life Support Systems Test Complex: Preliminary Designs and Considerations," SAE Technical Paper 1999-01-2188, 1999.
10) NASA, BIO-Plex Facility in Building 29, https://archive.org/details/JSC2001-00794, 2001.
11) F. B. Salisbury, W. Campbell, J. G. Carman, G. E. Bingham, "Plant growth during the greenhouse II experiment on the Mir orbital station," Advances in Space Research, 31 (1) 221-227, 2003.
12) M. E. Cook, J. G. Croxdale, "Ultrastructure of potato tubers formed in microgravity under controlled environmental conditions," Journal of Experimental Botany, 54(390) 2157-2164, https://doi.org/10.1093/jxb/erg218, 2003.
13) W. G. Stutte, O. Monje, D. G. Goins, C. B. Tripathy, "Microgravity effects on thylakoid, single leaf, and whole canopy photosynthesis of dwarf wheat," Planta 223 46-56, https://doi.org/10.1007/s00425-005-0066-2, 2005.
14) G. Massa, Food Production for Space Exploration, KSC-E-DAA-TN38634, 2017.
15) Environment and Ecology, Biosphere 2, http://environment-ecology.com/ecological-design/255-biosphere-2.html, 2018.10.14 Access.
16) The University of Arizona, Biosphere 2 Where science lives, http://biosphere2.org/, 2018.10.18 Access.
17) M. Sumiji, H. Miyajima, Y. Annou, K. Murakawa, Overview of Mars Simulation Experiments and Consideration of Manned Mars Exploration, International Journal of Microgravity Science and Application, 33 (3) 330311, http://doi.org/10.15011/ijmsa.33.330311, 2016.
18) YUSUKE MURAKAMI Official Website, http://www.fieldnote.net/about/, 2018.10.12 Access.
19) E. Brinckmann, ESA hardware for plant research on the International Space Station, Advances in Space Research, 36(7) 1162-1166, 2005.
20) D. Schubert, D. Quantius, J. Hauslage, L. Glasgow, F. Schroder, M. Dorn, Advanced Greenhouse Modules for use within Planetary Habitats, 41st International Conference on Environmental Systems, AIAA2011-5166, 2011.

21) ESA EDEN Ground Demonstration of Plant Cultivation Technologies for Safe Food Production in Space, http://eden-iss.net/, 2018.10.14 Access.

22) M. Shinohara, O. Komatsubara, Y. Aibe, S. Nozoe, T. Shimamiya, Y. Tako, K. Nitta, "Air Circulation Confinement Experiments in the CEEF: Physiological Status in Econauts through Repeated Seven-day Habitations," Society for Automotive and Engine Technology, Paper 2006-01-2293, 2006.

23) K. Nitta, "The CEEF, closed ecosystem as a laboratory for determining the dynamics of radioactive isotopes," Advances in Space Research, 27(9) 1505-1512, https://doi.org/10.1016/S0273-1177(01)00242-3, 2001.

24) Y. Tako, "Closed residency experiment using closed ecosystem experimental facilities: food self-sufficiency and substance (air, water and waste) cycling, and troubleshooting," Closed Ecosystem and Ecological Engineering Handbook 48-66, 2015.

25) S. Yano, H. Kasahara, D. Masuda, F. Tanigaki, T. Shimazu, H. Suzuki, I. Karahara, K. Soga, T. Hoson, I. Tayama, Y. Tsuchiya, S. Kamisaka, "Improvements in and actual performance of the Plant Experiment Unit onboard Kibo, the Japanese experiment module on the international space station," Advances in Space Research, 51(5) 780-788, 2013.

26) Science and Technology Council Research Planning and Evaluation Subcommittee Space Development and Utilization Subcommittee ISS / International Space Exploration Subcommittee (20th) Material 20-1-1 2017.6.28, http://www.mext.go.jp /b_menu/shingi/gijyutu/gijyutu2/071/shiryo/1387901.htm, 2017.

27) S. Yano, T. Shimazu, "Lighting technology required for plant cultivation in space," Japanese Journal of Optics, 46(1) 25-31, 2017.

28) C. Dong, Y. Fu, B. Xie, M. Wang, H. Liu, "Element cycling and energy and responses in ecosystem simulations conducted at the Chinese Lunar Palace-1," Astrobiology 17(1) 78-86, 2017.

29) "Lunar Palace" experiment completed: 370 days in total, the longest in the world (China News Service 2018.5.19), http://www.afpbb.com/articles/-/3175157, 2018.10.17 Access.

30) NASA is serious about growing plants on Mars. Designed an inflatable green house with space agriculture in mind, http://karapaia.com/archives/52238501.html, 2017.5.5.

31) A. Sinitskaya, On the ISS will grow green in cylindrical beds, https://iz.ru/737654/anastasiia-sinitckaia/na-mks-vyrastiat-zelen-v-tcilindricheskikh-griadkakh, 2018.7.17.

32) K. Soga, "Regulation of plant growth by gravity-A ground experiment using centrifugal hypergravity," Journal of the Japan Society of Microgravity Application 21(1) 74-78, 2004.

33) H. Takahashi, J. Hidema, Y. Kitaya, T. Hoson, I. Karahara, S. Yano, "A research scenario of space-utilizing plant science," International Journal of Microgravity Science and Application, 34 (2) 340200, 2017.

34) J. Kiss, "Plant biology in reduced gravity on the Moon and Mars," Plant Biology 16, suppl.1, 12-17, 2014.

35) Y. Kitaya, "Plant heat and gas exchange in plant cultivation in space," Closed Ecosystem and Ecological Engineering Handbook 86-92, 2005.

36) Y. Kitaya, "Plant cultivation system water cycling under microgravity from an aircraft parabolic flight experiment" 32nd Symposium on the Use of the Space Environment, 2018.

37) International Space Station, Space Station Research Experiments, Biology and Biotechnology, Plant Biology, https://www.nasa.gov/mission_pages/station/research/experiments/experiments_hardware.html#Biology-and-Biotechnology, Access 2018.8.7.

38) J. Croxdale, M. Cook, T. W. Tibbitts, C. S. Brown, R. M. Wheeler, "Structure of potato tubers formed during spaceflight," Journal of Experimental Botany, 48(317) 2037-2043, 1997.

39) M. Perchonok, The Challenges of Developing a Food System for Mars Mission, JSC-CN-36608, 2016.

40) J. Haipeng, Space Journal: Entry 7 -- Chinese farmers in space, http://www.xinhuanet.com//english/2016-11/13/c_135825974.htm, 2016.11.13.

3. SELECTION OF CROP SPECIES

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3. 1 Nutritional level required by a Japanese person on the moon

3.1.1 Premise of the nutrition level required by a Japanese person on the moon

The target of this working group was Japanese people. The nutritional intake standards for long-term stays on the ISS in space include NASA's planetary exploration missions, but these are considered mainly by Westerners and cannot be applied to Japanese people [1]. At present, the standards for planetary missions are generally in accordance with the US terrestrial standards[1], except for calcium and vitamin D, which emphasize nutritional significance in long-term missions and are used on lunar farms in this working group. Because the criteria for determining the number of crops cultivated in Japan is for Japanese people, we decided to utilize the "Japanese Dietary Intake Standards 2015 Edition" [2] (hereafter, Dietary Intake Standards) by the Ministry of Health, Labor and Welfare. Dietary Intake Standards are intended for healthy individuals and groups and indicate the standards for energy and nutrient intake to maintain and promote people's health and prevent lifestyle-related diseases by gender and age. The study was conducted based on the "meal intake standard" for men aged 30 to 49 (physical activity level 2) (Table 3.1).

Table 3.1 Reference Dietary Intake Values for Men and Women Aged 30–49 Years (Physical Activity Level 2)

			Men	Women	Tolerable upper intake level	Breastfeeding mothers and pregnant women (additional amount)
Calories	kcal/day	Estimated average requirement	2650	2000		
Protein	g/day	Recommended dietary allowance	60	50		
Tentative dietary goal for preventing life-style related diseases	% energy	Tentative dietary goal for preventing life-style related diseases	13–20	13–20		
Fat	% energy	Tentative dietary goal for preventing life-style related diseases	20–30	20–30		
Carbohydrates	% energy	Tentative dietary goal for preventing life-style related diseases	50–65	50–65		
Dietary fiber	g/day	Tentative dietary goal for preventing life-style related diseases	20 or more	18 or more		
Vitamin A	μRAE/day	Recommended dietary allowance	900	700	○	○
Vitamin D	μg/day	Adequate intake	5.5	5.5	○	○
Vitamin E	mg/day	Adequate intake	6.5	6.0	○	○
Vitamin K	μg/day	Adequate intake	150	150		
Vitamin B1	mg/day	Estimated average requirement—recommended dietary allowance	1.2–1.4	0.9–1.1		○
Vitamin B2	mg/day	Estimated average requirement—recommended dietary allowance	1.3–1.6	10–1.1		○
Niacin	mgNE/day	Estimated average requirement—recommended dietary allowance	13–15	8–11	○	○
Vitamin B6	mg/day	Estimated average requirement—recommended dietary allowance	1.2–1.4	1.0–1.2	○	○
Vitamin B12	μg/day	Estimated average requirement—recommended dietary allowance	2.0–2.4	2.0–2.4		○

Folacin	µg/day	Estimated average requirement—recommended dietary allowance	200–240	200–240	○	○
Pantothenic acid	mg/day	Adequate intake	5	4		○
Biotin	µg/day	Adequate intake	50	50		○
Vitamin C	mg/day	Estimated average requirement—recommended dietary allowance	85–100	85–100		○
Sodium	mg/day	Estimated average requirement	600	600		
(Sodium chloride equivalent)	g/day	Estimated average requirement	1.5	1.5		
Potassium	mg/day	Adequate intake	2500	2000		○
Calcium	mg/day	Estimated average requirement—recommended dietary allowance	550–650	550–650	○	
Magnesium	mg/day	Estimated average requirement—recommended dietary allowance	310–370	240–290		
Phosphorus	mg/day	Adequate intake	1000	800	○	○
Iron	mg/day	Estimated average requirement—recommended dietary allowance	6.0–7.0	9.0–10.5 (with menstruation)	○	○
				5.5–6.5 (without menstruation)		
Zinc	mg/day	Estimated average requirement—recommended dietary allowance	8–10	6–8	○	○
Copper	mg/day	Estimated average requirement—recommended dietary allowance	0.7–1.0	0.6–0.8	○	○
Manganese	mg/day	Adequate intake	4.0	3.5	○	○
Iodine	µg/day	Estimated average requirement—recommended dietary allowance	95–130	95–130	○	○
Selenium	µg/day	Adequate intake	25–30	20–25	○	○
Molybdenum	µg/day	Estimated average requirement—recommended dietary allowance	25–30	20–25	○	○

3.1.2 Indicators of energy and nutrients [2)]

Based on the Dietary Intake Standards, an index (estimated energy requirement) was determined for energy to avoid excess or a deficiency of energy intake. There were three types of indicators regarding nutrients to avoid insufficient intake (estimated average requirement, recommended dietary allowance, and adequate intake). There were also indicators to avoid health problems because of overdose (tolerable upper intake level) and indicators to prevent lifestyle-related diseases (tentative dietary goal for preventing lifestyle-related diseases), for a total of six indicators. The six indicators of energy and nutrients are explained in Table 3.2.

Table 3.2. Energy and Nutrient Indicators Demonstrated by Dietary Intake Standards

Index	
Estimated energy requirement	According to the WHO definition, energy requirements are defined as "energy intake that is balanced with energy expenditure when an individual of a certain height/weight and body composition is at a physical activity level that maintains good health for a long period.” Estimated Energy Requirement (kcal/d) = Basal Metabolic Rate (kcal/d) × Physical Activity Level
Estimated average requirement (EAR)	An average value of the required amount in the population is based on the distribution of the required amount measured in a target population and defined as an intake estimated to meet the requirements of 50% of people in the population.
Recommended dietary allowance (RDA)	The amount that satisfies most people (97–98%) in the population, based on the distribution of requirements measured in a target population.
Adequate intake (AI)	An “adequate intake’’ is defined as an amount sufficient to maintain an individual’s nutritional status in a specific population. It shall be calculated when the "estimated average requirement" cannot be calculated because of an insufficient chemical basis. In practice, it is given by the amount that is rarely observed in people who show a deficiency in a particular population.

Tolerable upper intake level (UL)	An amount that provides an upper limit on the habitual intake is considered not at risk of causing health problems. Ingestion beyond this will increase the risk of potential health problems caused by overdose. No set nutrients for which sufficient chemical basis cannot be obtained.
Tentative dietary goal for preventing life-style related diseases (DG)	Set as "the amount of intake that the current Japanese people should aim for to prevent lifestyle-related diseases."

3.2 Selection of crop candidates to cultivate

We will use a plant factory on the lunar farm that can grow crops with artificial light sources and no sunlight. In Japan, commercial cultivation using plant factories is the most widespread worldwide, and related research accumulation and technological development capabilities are among the highest. Because the artificial light-type plant factory developed in Japan can maintain a high degree of closure in the cultivation room, it is easy to control the energy and mass balance. The following points should be considered when selecting candidate crops for production on the moon using an artificial light-type plant factory.

3.2.1 Crop production in plant factories

The main food crops are cereals, legumes, potatoes, nuts and seeds, leafy vegetables, fruit vegetables, root vegetables, and fruit trees. The majority of edible crops can be produced in artificial light plant factories. The artificial light-type plant factory uses a hydroponic cultivation method instead of soil to control temperature and humidity, light, CO_2 gas, O_2 gas, and airflow, which are above-ground environmental factors necessary for plant growth.

Hydroponic cultivation is a method for cultivating plants by feeding them a culture solution containing necessary elements without using soil [3)]. Hydroponic cultivation can be broadly divided into solid medium cultivation that uses sand, rubble, sawdust, rock wool, perlite, vermiculite as the medium, hydroponics, and spray cultivation do not use a solid medium. Leafy vegetables can be cultivated by hydroponics, but many crops are cultivated by solid medium cultivation. Because gravity exists on the lunar surface (1/6 G), it is considered that the technology on the ground can be used for hydroponic cultivation almost in its current state.

3.2.2 Differences between crop species

The productivity (yield of one crop) in a plant factory is approximately 1 to 3 times that of conventional methods if the environmental conditions and cultivation conditions are optimized. In rice (paddy rice), it is possible to obtain twice the paddy fields' average yield. Additionally, because approximately three crops can be cultivated a year, the annual yield is approximately six times that of paddy fields [4)].

The electricity required for cultivation in a plant factory is mainly used for lighting and air conditioning. Because the efficiency of photosynthesis (sugar synthesis), which is the first step of substance synthesis in plants, can be regarded as almost the same regardless of the crop species[5)], the difference in the efficiency of dry matter weight growth per unit power input between plant species is considered to be small. However, the efficiency of the synthesis of proteins, lipids, and secondary metabolites varies among crop species.

Other crop species differences are the edible portion ratio (harvest index) and labor for cultivation management. A large ratio of edible parts indicates few non-edible parts become residue. There is a large difference between crop species in labor, such as cultivation management work and harvest. If cultivation management is complicated or requires a long time, the lunar resident's burden will increase. However, because the amount of labor can be solved by mechanization and robotization, which will be described later, it is not necessary to give much importance to selecting candidate crops regarding the work required.

3.2.3 Virus-freeing

To prevent the spread of viral plant diseases and fungal diseases in the lunar base, it is desirable to take virus-free crops from the earth and bring them to the lunar base. At present, they can be roughly divided into crops that can be virus-free and propagated by the plant tissue culture method and crops for which this technology has not been established. Therefore, it is desirable to focus on the selection of crops. It is also necessary not to bring pests from the earth. Considering the above, pesticide-free cultivation will be possible because an outbreak of pests could be suppressed on the lunar farm.

3.2.4 Traits

Pest resistance, environmental stress resistance, and high-water utilization efficiency emphasized in agricultural breeding are not required in plant factories. Rather, it is useful to determine varieties that exhibit rapid growth under suitable cultivation conditions in plant factories. It is also assumed that genetically modified crops with beneficial traits, such as high-speed growth in plant factories and high content of nutrients and functional components, will be used.

3.2.5 Mechanization, robotization, and ICT use

AI, ICT, mechanization, and robotization in the agricultural field are expected to make significant progress by the time the lunar base is in operation. Therefore, it is assumed that mechanization/robot technology, the possibility of which has already been suggested, could be introduced. It is assumed that robots will perform simple, painful, and dangerous farming tasks that humans dislike. Pollinating insects may be introduced, but if not, it is assumed that the robot will do so, including the spraying of hormones. However, it is necessary to develop elemental technologies to realize this.

Considering the above viewpoints and the dietary intake standards in Section 3.1, the following crops were selected as candidate crops:

Cereals	Rice
Legumes	Soybeans
Tubers	Potato and sweet potatoes
Fruit vegetables	Tomatoes, strawberries, and cucumbers
Leafy vegetables	Lettuce and others (e.g., Komatsuna)

These can be cultivated in a plant factory, made virus-free using a tissue culture method, and can be genetically recombined.

The main cereals are rice, wheat, and barley, but we chose rice to consider the variety of dishes possible, mainly Japanese food. Cultivation in a plant factory has abundant research examples. Among beans, soybeans are a popular crop that can be used as a staple food, side dish, and vegetable oil and can also be used as an ingredient in tofu and patties. Its cultivation in plant factories is abundant at the research level. In open-field agriculture, potatoes and sweet potatoes grow in the soil. There are many research examples of hydroponic cultivation of potatoes and other tubers. Sweet potatoes are an enlarged root, and they are somewhat difficult to cultivate in a hydroponic solution, but research and development are being conducted. Both are highly nutritious and indispensable crops for cooking; consequently, they were selected. We selected fruit vegetables and leaf vegetables produced in large quantities and have a high utility value as foodstuffs. We selected crop species that are popular and have many production cases in plant factories.

Other than the crops selected, there are nuts and seeds, root vegetables, fruit trees, and tea. These crops can be cultivated by any of the eight selected crop cultivation methods. Therefore, in this report, various studies will be reported using a combination of these eight crops.

3.2.6 Characteristics of the selected candidate crops [6)7)8)]

The nutritional characteristics of the selected candidate crops are as follows:

(1) Rice (Brown Rice)

The edible part of rice is the grain. Rice is high in carbohydrates, a major energy source, and a staple food. Brown rice is made by removing rice husks from grains. The bran and germ have more protein, lipids, minerals, and dietary fiber than refined rice, but its digestion and absorption rate is low.

(2) Potatoes

Potatoes are suitable for cultivation in cool climates. It is an important food worldwide because it can be harvested stably and has high storability. Because of its light taste, it is also commonly used as a staple food. The main ingredient is starch, rich in vitamin C, vitamin B1, and potassium. It is also called *pomme de terre* ("Apple of the Earth") in France. It is cultivated worldwide as a staple food vegetable.

(3) Sweet potatoes

Sweet potatoes were regarded as a salvage crop because they are resistant to weather changes and can be harvested stably. Among potatoes, it has a high sugar content and an intense sweetness. The main ingredient is starch, rich in minerals, such as vitamin C, vitamin E, potassium, calcium, copper, and dietary fiber. Leaves and stems can also be consumed.

(4) Soy

① Soybeans

Soybeans are rich in high-quality protein to the point where they have been referred to as the "meat of the field" and are rich in calcium, vitamin B1, vitamin B2, and vitamin E. Because soybeans have a rigid structure and poor digestion, they are made into various processed products, such as tofu, fried tofu, soymilk, miso, natto, fats and oils, and soy sauce.

② Green soybeans

Green soybeans refer to immature beans harvested before ripening. Like soybeans, they are rich in protein, sugar, vitamin B1, vitamin B2, calcium and contain vitamin C, which is not found in mature soybeans.

(5) Tomatoes (cherry tomatoes)

These are western vegetables of the Solanaceae family that complement dishes with bright colors. In Japan, they are often eaten raw and frequently used. Cherry tomatoes are small, sweet, juicy, and have moderate acidity. The red pigment is called lycopene and has antioxidant properties. It is a green-yellow vegetable that is relatively high in vitamin C and vitamin A and contains potassium.

(6) Cucumbers

Cucumbers are regular vegetables because they have a refreshing aroma and texture and can be eaten raw. Approximately 95% of the cucumber is water, and the remaining 4% contains a small amount of vitamins, minerals, and carbohydrates. It contains an enzyme called ascorbinase that destroys vitamin C (suppressed by acid).

(7) Lettuce (leaf lettuce)

Lettuce is a crisp, versatile vegetable that can be easily adapted to many dishes. Approximately 95% of the total is moisture and includes vitamins C and E, carotene, calcium, potassium, iron, and zinc. Compared with head lettuce, leaf lettuce has a higher potassium content, vitamins, and minerals.

(8) Strawberries

Strawberries can be eaten quickly after washing and have a favor that has refreshing sweetness and fragrance. Among the fruits, it contains a high vitamin C content, and the flesh is juicy and has a moderate sweetness and sourness.

Table 3.3 Nutritional value of the eight crop species (per 100 g) [9)]

	Calories (kcal)	Protein g	Fat g	Carbohydrates g	Dietary fiber g	Sodium mg	Potassium mg	Calcium mg	Magnesium mg	Phosphorus mg	Iron mg	Zinc mg	Copper mg	Manganese mg	Iodine µg	Selenium µg	Chromium µg	Molybdenum µg
1) Brown rice	353	6.8	2.7	74.3	3.0	1	230	9	110	290	2.1	1.8	0.27	2.06	0	3	0	64
Refined white rice	358	6.1	0.9	77.6	0.5	1	89	5	23	95	0.8	1.4	0.22	0.81	0	2	0	69
2) Sweet potatoes	134	1.2	0.2	31.9	2.2	11	480	36	24	47	0.6	0.2	0.17	0.41	1	0	1	4
3) Potatoes	76	1.6	0.1	17.6	1.3	1	410	3	20	40	0.4	0.2	0.10	0.11	0	0	5	4
4) Soybeans	422	33.8	19.7	29.5	17.9	1	1900	180	220	490	6.8	3.1	1.07	2.51	0	5	3	350
Edamame	135	11.7	6.2	8.8	5.0	1	590	58	62	170	2.7	1.4	0.41	0.71	0	1	1	240
5) Lettuce	16	1.2	0.2	3.2	2.0	4	410	66	15	31	1.8	0.4	0.05	0.43	0	0	0	0
6) Mini-tomatoes	29	1.1	0.1	7.2	1.4	4	290	12	13	29	0.4	0.2	0.06	0.10	4	0	0	4
7) Cucumbers	14	1.0	0.1	3.0	1.1	1	200	26	15	36	0.3	0.2	0.11	0.07	1	1	1	4
8) Strawberries	17	0.5	0.1	4.3	0.7	0	85	9	7	16	0.2	0.1	0.03	0.10	1	0	0	5

	Retinol activity equivalents µg	Vitamin D µg	α-Tocopherol mg	Vitamin K µg	Vitamin B1 mg	Vitamin B2 mg	Niacin mg	Vitamin B6 mg	Vitamin B12 µg	Folacin µg	Pantothenic acid mg	Biotin µg	Vitamin C Mg	Sodium chloride equivalent g
1) Brown rice	0	0.0	1.2	0	0.41	0.04	6.3	0.45	0.0	27	1.37	6.0	0	0.0
Refined white rice	0	0.0	0.1	0	0.08	0.02	1.2	0.12	0.0	12	0.66	1.4	0	0.0
2) Sweet potatoes	2	0.0	1.5	0	0.11	0.04	0.8	0.26	0.0	49	0.90	4.1	29	0.0
3) Potatoes	0	0.0	0.0	0	0.09	0.03	1.3	0.18	0.0	21	0.47	0.4	35	0.0
4) Soybeans	1	0.0	2.3	18	0.71	0.26	2.0	0.51	0.0	260	1.36	27.5	3	0.0
Edamame	22	0.0	0.8	30	0.31	0.15	1.6	0.15	0.0	320	0.53	11.1	27	0.0
5) Lettuce	170	0.0	1.2	160	0.10	0.10	0.3	0.08	0.0	120	0.14	0.0	17	0.0
6) Mini-tomatoes	80	0.0	0.9	7	0.07	0.05	0.8	0.11	0.0	35	0.17	3.6	32	0.0
7) Cucumbers	28	0.0	0.3	34	0.03	0.03	0.2	0.05	0.0	25	0.33	1.4	14	0.0
8) Strawberries	1	0.0	0.2	0	0.02	0.01	0.2	0.02	0.0	45	0.17	0.4	31	0.0

3.3 Determination of daily consumption quantity on the Lunar Farm [2)9)]

This working group proceeded with the study on the precondition that the plants cultivated on the lunar farm would be self-sufficient without relying on a supply from the earth. Based on each cultivated crop's nutrient characteristics, we aimed for the range indicated by the "dietary intake standard." The daily amount of the eight crop species was determined by considering the balance between energy and the three macronutrients.

For vitamins and minerals, we aimed for the recommended daily allowance (RDA) to the extent possible, and we adjusted the content by setting the target value in a range from the estimated average requirement (EAR) to the tolerable upper intake level (UL). Ultimately, 400 g of brown rice, 150 g of sweet potato, 75 g of potato, 120 g of soy (dried), 50 g of green soybean, 150 g of leaf lettuce, 200 g of tomato, 100 g of cucumber, and 50 g of strawberry were determined as the daily intake in this working group. Table 4 shows a comparison between the supply of the eight crop species and the standard value (* estimated average requirement, recommended dietary allowance, or adequate intake).

Table 3.4 Comparison of the amount of nutrients obtained from the eight crop species with the standard values based on the Japanese dietary intake standard (2015 version)

Food name	Weight (g)	Calorie kcal	Protein g	Fat g	Carbohydrates g	Dietary fiber g	Sodium mg	Potassium mg	Calcium mg	Magnesium mg	Phosphorus mg	Iron mg	Zinc mg	Iron mg	Manganese mg	Iodine µg	Selenium µg	Chromium µg	Molybdenum µg
Brown rice	400	1412	27.2	10.8	297.2	12	4	920	36	440	1160	8.4	7.2	1.08	8.24	0	12	0	256
Sweet potatoes	150	201	1.8	0.3	47.85	3.3	16.5	720	54	36	70.5	0.9	0.3	0.26	0.62	2	0	2	6
Potatoes	75	57	1.2	0.075	13.2	0.975	0.75	307.5	2.25	15	30	0.3	0.15	0.08	0.08	0	0	4	3
Soybeans (dried)	120	506	40.56	23.64	35.4	21.48	1.2	2280	216	264	588	8.16	3.72	1.28	3.01	0	6	4	420
Edamame	50	68	5.85	3.1	4.4	2.5	0.5	295	29	31	85	1.35	0.7	0.21	0.36	0	1	1	120
Soybean oil	30	276	0	30	0	0	0	0	0	0	0	0	0	0.00	0.00	0	0	0	0
Leaf lettuce	150	24	1.8	0.3	4.8	3	6	615	99	22.5	46.5	2.7	0.6	0.08	0.65	0	0	0	0
Mini-tomatoes	200	58	2.2	0.2	14.4	2.8	8	580	24	26	58	0.8	0.4	0.12	0.20	8	0	0	8
Cucumbers	100	14	1	0.1	3	1.1	1	200	26	15	36	0.3	0.2	0.11	0.07	1	1	1	4
Strawberries	50	17	0.45	0.05	4.25	0.7	0	85	8.5	6.5	15.5	0.15	0.1	0.03	0.10	1	0	0	5
Total	1325	2633	82.06	68.565	424.5	47.9	38	6003	495	856	2090	23.1	13.4	3.23	13.32	11	20	10	822
Standard value			P ratio (12%)	F ratio (23%)	C ratio (65%)			2500	650	370	1000	7.5	10	1	4	130	30	10	25
Sufficiency rate								240%	76%	231%	209%	307%	134%	323%	333%	8%	65%	104%	3286%
Evaluation			○	○	○	○	○	Excess	Deficiency	Excess	○	○	○	○	Excess	Deficiency	Deficiency	○	Excess

Food name	Retinol µg	Vitamin D µg	α-Tocopherol mg	Vitamin K µg	Vitamin B1 mg	Vitamin B2 mg	Niacin mg	Vitamin B6 mg	Vitamin B12 µg	Folacin µg	Pantothenic acid mg	Biotin µg	Vitamin C mg	Sodium chloride equivalent g
Brown rice	0	0.0	4.8	0	1.64	0.16	25.2	1.80	0.0	108	5.48	24.0	0	0.0
Sweet potatoes	3	0.0	2.3	0	0.17	0.06	1.2	0.39	0.0	74	1.35	6.2	44	0.0
Potatoes	0	0.0	0.0	0	0.07	0.02	1.0	0.14	0.0	16	0.35	0.3	26	0.0
Soybeans (dried)	1	0.0	2.8	22	0.85	0.31	2.4	0.61	0.0	312	1.63	33.0	4	0.0
Edamame	11	0.0	0.4	15	0.16	0.08	0.8	0.08	0.0	160	0.27	5.6	14	0.0
Soybean oil	0	0.0	3.1	63	0.00	0.00	0.0	0.00	0.0	0	0.00	0.0	0	0.0
Leaf lettuce	255	0.0	1.8	240	0.15	0.15	0.5	0.12	0.0	180	0.21	0.0	26	0.0
Mini-tomatoes	160	0.0	1.8	14	0.14	0.10	1.6	0.22	0.0	70	0.34	7.2	64	0.0
Cucumbers	28	0.0	0.3	34	0.03	0.03	0.2	0.05	0.0	25	0.33	1.4	14	0.0
Strawberries	1	0.0	0.2	0	0.02	0.01	0.2	0.02	0.0	45	0.17	0.4	31	0.0
Total	459	0.0	17.4	388	3.21	0.92	33.0	3.42	0.0	989	10.12	78.0	221	0.0
Standard value	900	5.5	6.5	150	1.4	1.6	15	1.4	2.4	240	5	50	100	
Sufficiency rate	51%	0%	268%	258%	230%	57%	220%	244%	0%	412%	202%	156%	221%	
Evaluation	Deficiency	Deficiency	○	Excess	Excess	Deficiency	○	○	Deficiency	○	Excess	Excess	Excess	

3.4 Necessary cultivation area

Considering the cultivation data, such as growth and yield assumed in plants and the harvest index (H. I.) of the edible part, the required area is as follows:

Table 3.5. Examples of calculating the required cultivation area

	Amount required per person	Productivity in the plant factory			Area required per person	Area required	
		Production per crop	Days needed for cultivation	Daily production		For 6 people	For 100 people
	(g/day)	(g/m^2)	(day)	($g/m^2/day$)	(m^2)	(m^2)	(m^2)
Rice	400	900	90	10	40.0	240	4000
Potatoes	75	8000	360	22	3.4	20	338
Sweet potatoes[1)]	150	–	–	20	7.5	45	750
Soybeans	350	1400	100	14	25.0	150	2500
Lettuce	150	2500	30	83	1.8	11	180
Tomatoes	200	83000	360	231	0.9	5	87
Cucumbers	100	70000	360	194	0.5	3	51
Strawberries	50	17000	360	47	1.1	6	106

[1)] Since there are not enough examples of sweet potato cultivation, the daily production is assumed to be about 90% of that of potatoes.

3.5 Nutrients that may be in excess

Nutrients that can be in excess (more than twice the estimated average requirement or recommended dietary allowance) are potassium, magnesium, vitamin K, vitamin B1, pantothenic acid, vitamin C, copper, α-tocopherol, niacin, vitamin B6, folic acid, iron, manganese, and molybdenum, for a total of 14 nutrients.

Table 3.6 Nutrients that are more than twice the estimated average requirement or recommended dietary allowance (excluding nutrients below the upper level)

<No tolerable upper limit dose>

Food name	Potassium mg	Magnesium mg	Vitamin K µg	Vitamin B1 mg	Pantothenic acid mg	Vitamin C mg
Total daily nutritional value	6003	856	388	3 .21	10 .12	221
Standard value	2500	370	150	1.4	5	100
Sufficiency rate	240%	231%	258%	230%	202%	221%
Tolerable upper limit	-	-	-	-	-	-
Evaluation	Excess	Excess	Excess	Excess	Excess	Excess

<Upper limit of tolerated dose>

Food name	Copper mg	α-Tocopherol mg	Niacin mg	Vitamin B6 mg	Folacin µg	Iron mg	Manganese mg	Molybdenum µg
Total daily nutritional value	3 .23	17 .4	33 .0	3 .42	989	23 .1	13 .32	822
Standard value	1	6.5	15	1.4	240	7.5	4	25
Sufficiency rate	323%	268%	220%	244%	412%	307%	333%	3286%
Tolerable upper limit	10	900	350	60	1000	55	11	550
Evaluation	Excess	Excess	Excess	Excess	Excess	Excess	Excess	Excess

One clear issue from comparing the nutrients based on the supplements of the eight crop species with the "dietary intake standard" is that manganese and molybdenum exceed the tolerable upper limit.

Manganese is present in an adult's body at an amount of 12 to 20 mg and is important in enzyme composition, such as manganese superoxide dismutase, and enzyme activation, such as arginase. It is involved in bone metabolism, glycolipid metabolism, motor function, and skin metabolism. Manganese is abundant in cereals, vegetables, and legumes, and overdose may occur because of peculiar dietary forms, such as strict vegetarian diets, improper use of supplements, and a tolerable upper level has been set. Because manganese is unevenly distributed on the bran side, it can be reduced by 5.0 mg by milling rice (Fig. 3.1). The rice milling process may be necessary to prevent hypervitaminosis.

Furthermore, molybdenum functions as a coenzyme for xanthine oxidase, aldehyde oxidase, and sulfite oxidase. Because molybdenum is also abundant in cereals and legumes, the intake is high in an extremely vegetarian diet. When molybdenum is compared between brown rice and white rice, there is no apparent difference, and it has been reported that molybdenum is distributed almost uniformly throughout the rice [7]; consequently, molybdenum is not expected to decrease by rice milling. However, because it has been clarified that the concentration of trace minerals, such as molybdenum, in plant foods fluctuate depending on the soil and

variety, it is necessary to consider the composition of the nutrient solution.

	Manganese mg
Brown rice: 400 g	8.24
Total for seven crop types	5.08
Total	13.32

	Manganese mg
White rice: 400 g	3.24
Total for seven crop types	5.08
Total	8.32

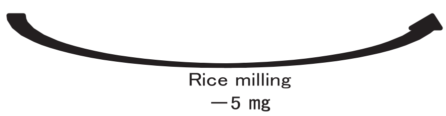

Fig. 3.1. Changes in manganese content caused by rice milling

There are 12 nutrients supplemented by the eight crop species supplement that are more than twice the estimated average requirement or recommended dietary intake. These are considered to have a low risk of health problems because there is no tolerable upper intake level, or they are below the tolerable upper intake level. However, in the space environment, there is a concern that iron may cause tissue damage as an oxidant because of exposure to space radiation; consequently, caution is required regarding excessive intake of iron [1]. Additionally, among nutrients that may be excessive, such as folic acid, the contents of nutrients other than vitamin K and vitamin C are reduced by rice milling (Table 3.7). Only niacin is slightly below the standard value, but there are concerns regarding health risks because of overdose, such that it is necessary to prioritize reducing the risk of overdose. As with molybdenum and manganese, it is necessary to conduct the rice milling process and to proceed with studies, including the composition of the cultivated nutrient solution.

Additionally, a tolerable upper intake level has not been set for dietary fiber and potassium. However, it is difficult to address these nutrients because there are few studies regarding excessive intake because they are easily deficient in modern times. However, careful consideration is required because even nutrients that do not have a tolerable upper intake level are significantly different from life on earth.

Table 3.7 Nutritional Value Changes by Rice Refining

	Weight g	Calorie kcal	Potassium mg	Magnesium mg	Iron mg	Copper mg	α-Tocopherol mg	Vitamin K µg	Vitamin B1 mg	Niacin mg	Vitamin B6 mg	Folacin µg	Pantothenic acid mg	Vitamin C mg
Brown rice 400 g + seven crop species	1325	2633	6003	856	23.1	3.23	17.4	388	3.21	33.0	3.42	989	10.12	221
Sufficiency rate			240%	231%	307%	323%	268%	258%	230%	220%	244%	412%	202%	221%
White rice 400 g + seven crop species	1325	2653	5439	508	17.9	3.03	13.0	388	1.89	12.6	2.10	929	7.28	221
Sufficiency rate			218%	137%	238%	303%	200%	258%	135%	84%	150%	387%	146%	221%
Impact of rice milling			Decrease	Decrease	Decrease	Decrease	Decrease	None	Decrease	Decrease	Decrease	Decrease	Decrease	None

3.6 Nutrients that may be in shortage

Comparing the dietary intake standards of Japanese people with the amount of supplements from the eight crop species, seven nutrients, including calcium, iodine, selenium, vitamin A (retinol), vitamin D, vitamin B2, and vitamin B12 (sodium is not supplied with vegetables, but it is excluded because it can be expected to be ingested from seasoning during cooking), are less than the estimated average requirement or recommended dietary allowance.

There are a few green and yellow vegetables on the lunar farm, and there is no supply of animal foods (fish, meat, dairy products), such that there may be a shortage of nutrients specifically contained in these foods. Above all, muscle and bone mass are reduced in the space environment; therefore, it is necessary to pay attention to calcium and vitamin D. Nutrients that are deficient in the supplementation from the eight crop species need to be ingested as supplements. The amount of nutrients deficient compared with the standard is 158.9 mg (Table 3.9). Astronauts bring along vitamin D supplements, and these nutrients need to be supplemented to avoid the risk of deficiencies.

Table 3.8 Inadequate Nutrients Table (Left) / 3.9 Inadequate Nutrient Levels (Right)

Food name	Weight g	Calcium mg	Iodine μg	Selenium μg	Retinol μg	Vitamin D μg	Vitamin B2 mg	Vitamin B12 μg
Brown rice	400	36	0	12	0	0.0	0.16	0.0
Sweet potatoes	150	54	2	0	3	0.0	0.06	0.0
Potatoes	75	2.25	0	0	0	0.0	0.02	0.0
Soybeans (dried)	120	216	0	6	1	0.0	0.31	0.0
Edamame	50	29	0	1	11	0.0	0.08	0.0
Soybean oil	30	0	0	0	0	0.0	0.00	0.0
Leaf lettuce	150	99	0	0	255	0.0	0.15	0.0
Mini-tomatoes	200	24	8	0	160	0.0	0.10	0.0
Cucumbers	100	26	1	1	28	0.0	0.03	0.0
Strawberries	50	8.5	1	0	1	0.0	0.01	0.0
Total	1325	495	11	20	459	0 .0	0 .92	0 .0
Standard value		650	130	30	900	5.5	1.6	2.4
Sufficiency rate		76%	8%	65%	51%	0%	57%	0%
Evaluation		Deficiency	Deficiency	Deficiency	Deficiency	Deficiency	Deficiency	Deficiency

	Supply amount	Standard value	Deficient amount	(mg)
Calcium (mg)	495	650	155	155
Iodine (μg)	11	130	119	0.119
Selenium (μg)	20	30	10	0.01
Retinol (μg)	459	900	441	0.441
Vitamin D (μg)	0	5.5	5.5	0.0055
Vitamin B2 (mg)	0.92	1.6	0.68	0.92
Vitamin B12 (mg)	0	2.4	2.4	2.4
			Total (mg)	158.9

3.7 Image of a meal using the eight crop species

With the supplied amount of the eight crop species determined in Section 3.3, a daily meal image was created with reference to general home cooking.

Table 3.10 Daily food image

	Dish name	Photograph	Calories kcal	Protein g	Fat g	Carbohydrates g	Dietary fiber g	Sodium chloride equivalent g
Morning	Rice		469	9.0	3.6	98.8	4.0	0.0
	Cooked beans		156	10.8	5.9	15.7	5.4	1.3
	Gojiru soup		59	4.5	2.5	4.9	2.2	1.1
	Chinese marinated salad		71	1.9	4.2	7.7	1.8	0.9
	Strawberries		17	0.5	0.1	4.3	0.7	0.0
	Total		773	26.8	16.2	131.4	14.1	3.3
Lunch	Soybean curry		860	27.4	28.2	124.2	13.9	1.6
	Sweet vinegar marinated lettuce		31	0.9	0.2	6.5	1.1	0.0
	Total		891	28.3	28.4	130.7	15.0	1.6
Snack	Sweet mashed potato		117	0.7	0.4	27.8	2.1	0.1
	Total		117	0.7	0.4	27.8	2.1	0.1
Dinner	Rice		469	9.0	3.6	98.8	4.0	0.0
	Soybean hamburger steak		433	15.9	23.1	41.3	9.2	2.0
	Boiled sweet potatoes		128	0.7	0.4	30.8	2.1	0.1
	Tomato soup		14	0.6	0.1	3.3	0.8	1.0
	Edamame		34	2.9	1.6	2.2	1.3	0.0
	Total		1078	29.2	28.7	176.4	17.3	3.1
Total for the day			2859	84.9	73.6	466.2	48.4	8.1

A separate recipe was created for the stems and leaves of sweet potatoes since they are edible.

Table 3.11 Sweet potato stem and leaf dishes

Boiled	Kinpira	Buchimgae-style	Chinese stir-fry
		 (Use of grated potatoes to bind)	

The stems and leaves of sweet potatoes are rarely eaten in Japan, but there is no problem doing so, and they can be eaten after cooking for a short time. The Japanese Food Standard Food Composition Table 2015 (7^{th} edition) does not describe the nutritional value of sweet potato stems and leaves, and the exact nutritional value is unknown; therefore, an analysis is required.

3.8 Limitations to nutrient intake based on ingredients from the crop species alone

The dietary environment of the eight crop species is very different from the dietary environment on earth. In particular, there is a wide variety of foods on earth, and the rich dietary environment contributes to the supply of nutrients and mental health. Animal foods, such as meat, fish, eggs, dairy products, and foodstuffs, such as mushrooms, fruit, and seaweed, were excluded from this study, but there is no record of living on a diet of only eight vegetable foods. Many aspects need to be explained.

Space food is created across 16 cycles, but astronauts are demanding regarding the diversification of the menu[11)], and Masuda et al. has stated that it is impossible to conduct long-term closed residence experiments while keeping human psychological stress low with only a few types of crops[12)]. To aim for a long-term stay, it is essential to increase the variety of diets by increasing the number of cultivated items and introducing livestock, such as cattle, pigs, chickens, or fish in the future.

3.9 Summary

It was possible to satisfy the three macronutrient requirements of carbohydrates, proteins, and fat, including energy, with the eight target crop species. However, the problem is the excess and deficiency of vitamins and minerals. There are 14 possible excess nutrients, including manganese and molybdenum. Because there are concerns about health risks caused by overdose, it is necessary to prioritize health risk reduction over deficient nutrients. As a coping method, the rice bran/germ is removed by rice polishing, and the composition of the cultivated nutrient solution is changed.

The deficient nutrients are calcium, iodine, selenium, vitamin A (retinol activity equivalent), vitamin D, vitamin B2, and vitamin B12. The reason is that there are no animal foods, seaweed, mushrooms, or green and yellow vegetables on the lunar farm. Because it is difficult to supply these from the eight crop species examined, supplementation is essential. The amount of supplement required is approximately 158.9 mg/d.

This study was conducted based on men aged 30 to 49 (physical activity level 2); however, other ages or women need to be examined separately.

Citations

1) A. Matsumoto, "Nutrition in space" Aeronautical Environmental Medicine, Vol.45, No.3, 75-97, 2008.
2) Japanese Dietary Intake Standards (2015 edition), Ministry of Health, Labor and Welfare
3) All aspects of nutrient solution cultivation, Japanese Greenhouse Horticulture Association and Japan Solution Cultivation Study Group, Co-eds., Seibundo, 2012.
4) Eiji Goto, Production of pharmaceutical materials using genetically modified plants grown under artificial lighting. Acta Hort. 907: 45-52. 2011.
5) Eiji Goto, Photosynthesis and Material Production of plants in artificial environment, TechnoInnovation, 16(4):18-22, 2006.
6) New visual food ingredient list with food commentary, Meeting to Think About New Eating Habits. Taishukan Shoten, 2016.
7) Vegetable and Fruit Item Guide, Haruna Shimomura, Agricultural Newspaper, 2014.
8) Convenient book of delicious vegetables for the body, Toshitaka Sakaki, Takahashi Shoten, 2008.
9) Japan Food Standard Food Composition Table 2015 (7th edition), Ministry of Education, Culture, Sports, Science and Technology.
10) Y. Qi, C. Shimojo, M. Yoshida, "Manganese and Molybdenum contents in rice", Biomedical Research on Trace Elements 26(1), 23-26, 2015.
11) S. Tachibana, T. Nakazawa, K. Shibukawa, "Stress factors under space environment and space food", Journal of the Japanese Society of Food Science and Engineering, Volume 55, Issue 12, December 2008.
12) T. Masuda, Y. Tako, “Preparation status for closed habitation experiment (1): food supply on the closed ecology experiment facilities (CEEF)”, Eco-Engineering, 17 (3), 183-189, 2005.

4. CULTIVATION SYSTEM

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Because spatial volume and energy consumption are limited in plant cultivation in space, it is necessary to increase plant density while simultaneously increasing lighting efficiency. Light-emitting diodes (LEDs), which have excellent luminous efficiency, durability, and safety, and are capable of accurate wavelength control over a wide range, are used as light sources. The environment, such as temperature and humidity, is controlled to the general optimum value on earth, and CO_2 concentration is controlled to 0.7 to 1 mmol mol^{-1}.

To establish environmental control technology for efficient plant production using space plant cultivation equipment, physical environmental factors for gas exchange and plant growth (light intensity, light-dark period, light wavelength, temperature, humidity, CO_2 concentration, airflow, medium moisture, and medium aeration), as well as the effects of space-specific environmental conditions, such as microgravity and a low-pressure environment, must be considered.

An environmental control that maximizes the photosynthetic rate is important in plant production. Here, we first examined the control of environmental factors common to plant production on earth, the effects of major physical environmental factors on photosynthesis, and environmental control issues under the microgravity of the universe.

4.1 Basic points to remember regarding the control of the crop cultivation environment on the lunar farm

4.1.1 Light environment

Because the spatial volume and energy consumption are limited in plant cultivation in space, it is necessary to increase plant density while increasing lighting efficiency. The light source uses an LED with excellent luminous efficiency, durability, and safety and is capable of accurate wavelength control over a wide range. The effective photosynthetic photon flux density (PPFD) for leaf vegetables, fruit vegetables, grains, and potatoes is 100–300, 200–500, 400–800, and 200–400 μmol m^{-2} s^{-1}, respectively. It is necessary to change the conditions depending on the plant species and varieties and the purpose of cultivation regarding light quality.

4.1.2 Temperature environment

Plant body temperature (or leaf temperature) directly affects biochemical reactions and physiological functions in plants. For example, the photosynthetic reaction has an optimum temperature, and in general, the leaf temperature at which the net photosynthetic rate is maximized is in the range of 20 to 30°C. Leaf temperature increases with increasing radiant energy absorbed by the leaves and decreases with increasing sensible and latent heat energy transported from the leaves to the surrounding air. Therefore, environmental factors (light intensity, temperature, humidity, and air velocity) involved in these energy balances affect leaf temperature, which subsequently affects photosynthesis and growth. Therefore, the concept of combined environmental control is important.

4.1.3 Moisture environment

The relationship between relative humidity and net photosynthetic rate varies with other environmental conditions (e.g., air velocity), but generally, the net photosynthetic rate is maximal at 75%–85% relative humidity. When the relative humidity reaches 90%, the net photosynthetic rate decreases, which means that under high relative humidity (low water vapor saturation), water loss because of transpiration is suppressed, and simultaneously, water absorption caused by root pressure is maintained. Therefore, it is speculated that under high relative humidity, the water vapor in the leaves becomes excessive, and the stomatal opening becomes small because of the pressure.

4.1.4 CO_2 environment

Generally, the net photosynthetic rate increases as the CO_2 concentration increases, but the net photosynthetic rate does not increase when the CO_2 saturation point is exceeded. The effect of CO_2 concentration on plant photosynthesis varies greatly depending on other environmental factors, such as light intensity and temperature. The CO_2 saturation point rises as light intensity increases. The CO_2 compensation point (CO_2 concentration when the net photosynthetic rate becomes zero) decreases as light intensity increases. As the CO_2 concentration increases, the effect of leaf temperature on the net photosynthetic rate becomes significant, and the leaf temperature that maximizes the net photosynthetic rate shifts to a higher temperature. Under low CO_2 concentration, even if the leaf temperature is increased to stimulate photosynthetic enzyme activity, the amount of CO_2, a required material for photosynthesis, is a limiting factor. Consequently, the effect of increasing the leaf temperature on the increase in the rate of net photosynthesis is minimal.

4.1.5 Airflow environment

It is necessary to circulate the air in the cultivation space to create uniform environmental conditions in the cultivation space and increase the net photosynthetic and transpiration rates to promote growth. When the air velocity decreases, leaf boundary layer resistance increases, photosynthesis (Fig. 4.1) and transpiration are suppressed, and consequently, growth is suppressed. When the air velocity around the plant is 0.5 m s^{-1} or less, growth suppression is remarkable as the air velocity decreases. The air velocity around plants that are growing close together is often 0.1 m s^{-1} or less. Additionally, control of the airflow environment is important because many environmental factors affect the photosynthesis and transpiration of crops through the foliar boundary layer.[1)]

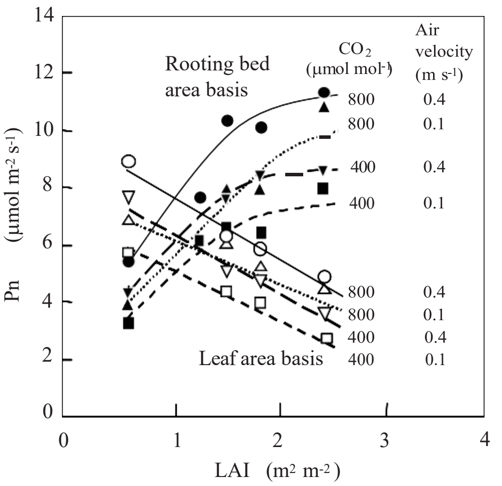

Fig. 4.1.
Effects of the leaf area index (LAI) on net photosynthetic rates (Pn) based on the rooting bed area (solid symbols) and the leaf area (open symbols) of tomato seedling canopies under different air velocities above the canopies and atmospheric carbon dioxide (CO_2) concentrations (from Kitaya et al., 2004 [2)]). Photosynthetic photon flux density: 250 µmol m^{-2} s^{-1}; air temperature: 23 °C; relative humidity: 55%; plant height: 0.05–0.2 m.

4.1.6 Rhizosphere environment

Generally, nutrient composition, pH, and liquid temperature are controlled in a nutrient solution tank. However, the environmental gas regulation is not sufficient in the nutrient solution tank alone. Especially in hydroponics, wherein the roots are always in the nutrient solution, the concentration of O_2 dissolved in the solution is often a limiting growth factor. For example, the maximum amount of O_2 that can be dissolved in 1 L of water at 20°C is 9.3 mg, consumed in a short time by root respiration. Therefore, to maintain normal root function, it is necessary to supplement O_2 in the nutrient solution continually. In particular, when the liquid temperature rises, the roots' respiration rate increases, O_2 consumption increases, and the saturated O_2 concentration in the liquid decreases, such that O_2 deficiency is likely to occur. To increase the amount of O_2 supplied to the roots, various measures have been used in the liquid feeding method and the cultivation bed structure. Because the O_2 diffusion coefficient in still water is approximately 1/10,000 in still air, the concentration immediately decreases when O_2 is absorbed in the vicinity of the roots in hydroponics. In hydroponics, where the roots are always in the culture medium, the O_2 concentration around the roots tends to decrease; therefore, it is important to forcibly increase the nutrient solution flow to transport O_2 to the root surface quickly. In spray tillage, the supply of O_2 to the roots is not restricted.

4.2 Plant cultivation under microgravity in space

4.2.1 Problems in controlling the environment for plant cultivation under space microgravity

The microgravity of space is simulated in many pseudo-microgravity experiments using a device (clinostat) that rotates a plant placed horizontally on the ground, which disturbs the direction of gravity. Plant physiology research on gravitropism has been conducted using space shuttles, and research has shown that plants can grow even under microgravity. An experiment was conducted in which plants were hung upside down such that the direction of gravity was the opposite of that on earth (gravity of −1 *g*) at a light intensity of 200 µmol m^{-2} s^{-1}. The results showed that even with gravity in the opposite direction to normal, the plant's growth direction could be controlled by phototropism (Fig. 4.2) and the plant could be grown almost normally [3)]. Long-term cultivation tests at the

International Space Station have recently demonstrated that plants can be cultivated even under the microgravity of space, blooming and bearing fruit.

To date, the reproductive processes of wheat and *Arabidopsis thaliana* analyzed in space experiments showed that although flowering and fruiting occurred, the formation rate of fertile seeds with germination ability was significantly reduced. For mustard seeds, the number of seeds was almost equal to that on the ground. Although they could be developed, there were reports that mutations occurred in seed traits and during the maturation process [4), 5), 6)]. There are many unclear aspects regarding the causes of these abnormalities.

The cultivation in space of plants like cereals and beans for human consumption is essential, and to produce these crops, it is necessary for normal reproductive growth, such as flowering and fertilization, to occur in space. To support long-term manned activities, the life cycle of seed germination, vegetative growth, reproductive growth, and seed formation must be repeated for generations. However, from the results of space experiments to date, it is expected that there might be problems with the reproductive growth and seed formation of plants, which do not function normally, as described above.

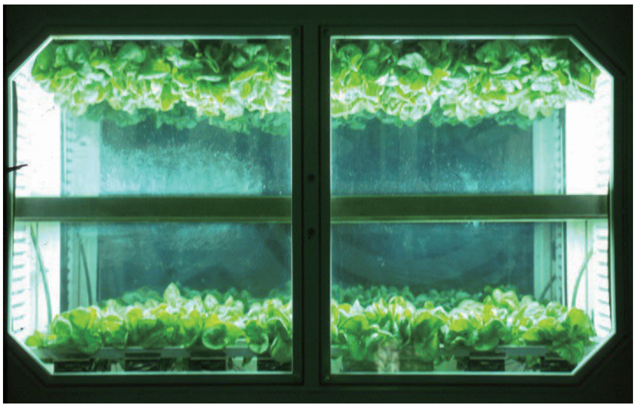

Fig. 4.2. Upside down cultivation of lettuce in the ground based experiment (Kitaya et al., 1992)

4.2.2 Effects of space microgravity on heat and gas exchange in plant leaves

Heat convection does not occur because of temperature differences in the microgravitational field of space, therefore it is thought that the exchange rate of heat and gas is significantly suppressed, resulting in increased temperature in plant organs and suppression of photosynthesis in leaves. Here, to investigate the effects of microgravity on leaf heat and gas exchange, we introduce results of an investigation on leaf temperature changes and the net photosynthetic rate of leaves caused by changes in gravity (0.01 to 2 G) during parabolic flight of an aircraft.

In one parabolic flight, from level flight at gravity 1 G, through ascending acceleration flight (2 G) for approximately 20 s, and microgravity flight (0.01 G) for approximately 20 s, the leaves received 1.5 G of gravity for approximately 30 s when returning to level flight. Fig. 4.3 shows the leaf temperature distribution of fresh barley leaves during the horizontal flight (gravity 1 G), ascending acceleration flight (2 G), microgravity flight (0.01 G), and 1.5 G before returning to horizontal flight [7)]. The leaf temperature distribution was acquired with an infrared thermal image camera. When gravity increased from 1 to 2 G, the high-temperature region in the leaf center decreased. At 0.01 G, the high-temperature region increased; and at 1.5 G, it further decreased. The average leaf temperature was approximately 30°C during level flight but decreased by approximately 0.3°C during ascending acceleration flight. After the start of microgravity flight, the leaf temperature increased linearly, and after 20 s, it had increased by approximately 1°C from the leaf temperature at 1 G. As gravity increased when returning to level flight, leaf temperature decreased again. Under microgravity, the leaf temperature in the thin part at the tip of the leaf increased by 2 to 3°C, and the increase in leaf temperature was remarkable compared to that in the wide part of the leaf [8)]. Convection occurred under 1 G gravity, and the leaf surface boundary layer at the narrow part of the tip of the leaf was thinner than that at the wide part of the leaf, thus the resistance to heat (latent heat + sensible heat) transport was small. Leaf temperature in thin areas was lower than that in large areas. However, under microgravity without convection, the thickness of the leaf surface boundary layer was almost constant regardless of the leaf width, such that the leaf temperature approached the same value regardless of the leaf width. Therefore, when the gravity dropped from 1 to 0.01 G, the increase in temperature in the thin parts became very high, and the temperature distribution on the leaf surface became uniform.

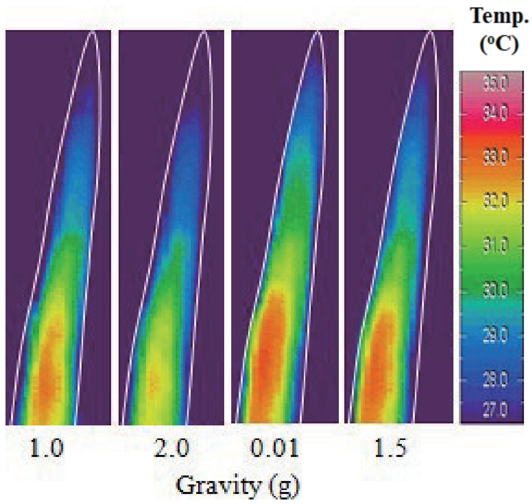

Fig. 4.3
Thermal images of the barley leaf at different gravity levels (from Kitaya et al., 2003 7)). Ambient air temperature: 28°C, Irradiance: 260 W m−2, Air velocity: 0.2 m s−1.

Fluctuations in the average surface temperature of the fresh barley leaves, a simulated copper plate leaf, and a simulated wet filter paper leaf with the change in gravity were compared by the same method as in the above experiment. The emissivity of each simulated leaf (the ratio of the energy of the radiation emitted from an object at a specific temperature to the energy of the radiation emitted from a blackbody at the same temperature, which is the same value as the emissivity), and heat capacity was almost the same as that of the fresh leaves. The evaporation or transpiration rates were higher in ascending order: copper plate simulated leaves < fresh barley leaves < wet filter paper simulated leaves. The temperature increase of each sample caused by the decrease in gravity from 1 to 0.01 G was 0.1°C for the copper plate simulated leaves, 0.8°C for fresh leaves, and 1.1°C for the filter paper simulated leaves, and the order of the temperature increase was consistent with the evapotranspiration rate of the materials. From this, it was concluded that in the heat exchange process of each sample in the microgravitational field, the temperature increase was greater with decreased evapotranspiration rate, and the latent heat transport was suppressed because of the suppression of convection.

The effects of gravity on the net photosynthetic rate of barley leaves and the transpiration rate of strawberry leaves are shown in Fig. 4.4 [7), 8), 9), 10)]. The net photosynthetic rate of barley leaves, which was approximately 4 $\mu mol\ m^{-2}\ s^{-1}$ during level flight, decreased at the beginning of microgravity flight (gravity 0.01 G), and after 20 s, decreased by 20% relative to that of level flight (gravity 1 G). The net photosynthetic rate sharply increased as gravity increased in return to level flight. The transpiration rate of strawberry leaves during microgravity flight was reduced by approximately 40% when compared with that during level flight.

Because heat convection does not occur because of the temperature difference in the microgravitational field, heat and gas exchange between the leaves and the surrounding air is suppressed, leaf temperature increases, and the net photosynthetic rate decreases with a decrease in transpiration rate. In this experiment, the microgravity period was as short as 20 s, and heat and gas exchange were not in a steady state. When a plant is placed under microgravity for an extended time, such as in a plant experiment in space, it is predicted from the plant's thermal characteristics that the increase in leaf temperature will be approximately twice that in this experiment where microgravity was only maintained for 20 s. Additionally, the decrease in net photosynthesis and transpiration rates will be even more remarkable under the continuous microgravity of space.

Increased plant body temperature and decreased net photosynthetic rate under microgravity are important issues to consider when producing plants in space. How are photosynthesis, transpiration, and leaf temperature affected in plants subject to the universe's microgravity for long periods? For example, pollen formation of rice, wheat, and tomato is impaired by a high temperature of approximately 32 to 34°C.

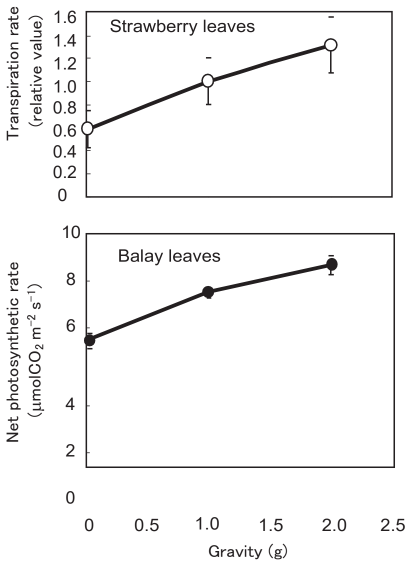

Fig. 4.4
Effects of gravity levels on photosynthetic rates (Pn) of barley leaves 20 s after exposure to each gravity level in airplane parabolic flight experiments (from Kitaya et al., 2001[9)]; Hirai & Kitaya, 2009 [10)]). Each value is the mean of four parabolic flights. Vertical bars represent standard deviations.

Therefore, we

investigated the temperature dynamics of the reproductive organ microtissue when heat convection does not occur under microgravity using an aircraft parabolic flight experiment. This experiment was used to predict the effects of microgravity on pollen formation and development with the temperature increase of the reproductive organs of plants. Thus, we examined the effects of the space environment on the reproductive growth of plants. The temperatures of rice stamens and stamen anthers, and tomato petals and pistil stigmas decreased when gravity increased from 1 to 2 G and increased when gravity decreased to 0.01 G (Fig. 4.5). As the gravity decreased from 1 to 0.01 G, the temperature of rice stalks increased by 2°C, that of stamen anthers increased by 3.6°C, that of tomato petals increased by 2.7°C, and that of pistil stigma increased by 2.4°C. The increase of the surface temperature of each part of the plant caused by the decrease in gravity became particularly remarkable in the delicate parts, such as the stamen anthers of rice. This experiment suggests that elevated temperatures might cause reproductive organ abnormalities in the absence of thermal convection under microgravity. From the above, it was concluded that microgravity suppresses gas exchange, such as in photosynthesis and transpiration, causing suppression of vegetative growth. Furthermore, the suppression of substance production and an increase in the temperature of reproductive organs caused by the suppression of photosynthesis are thought to cause abnormal reproductive growth, such as sterility (Fig. 4.6). Appropriate airflow environmental control is indispensable to prevent such growth suppression and reproductive abnormalities.

As described above, heat convection (density convection) is unlikely to occur under microgravity. Therefore, in the absence of forced airflow, even for 20 s of microgravity (0.01 G) generated during parabolic flight, heat exchange between plant leaves and ambient air was suppressed by decreased heat convection, and a leaf temperature increase of approximately 2 to 3°C can occur. Especially under microgravity, the suppression of latent heat exchange by suppressing transpiration is intimately involved in increasing leaf temperature. The suppression of convection under microgravity also reduces the CO_2 absorption rate (net photosynthetic rate) of the leaves. Therefore, from the viewpoint of heat and gas exchange, convection promotion by airflow control is indispensable in plant cultivation in space. When attempting to fertilize seeds in space for sustainable plant production, it is necessary to force air flow around the plant to promote heat and gas exchange in the reproductive organs to prevent excessive temperature increases of the reproductive organs that cause reproductive abnormalities. Additionally, because the air velocity is low in a high-density plant community, airflow control is indispensable for promoting gas diffusion, photosynthesis, and transpiration.

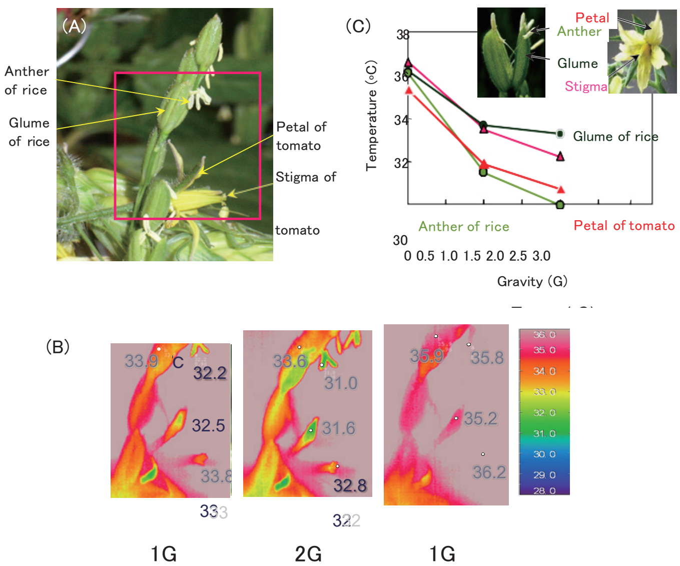

Fig. 4.5 Effects of gravity on the surface temperature of plants (Kitaya and Hirai, 2013). (A) Photograph of the measurement site; (B) Thermal images under different levels of gravity (1, 2, and 0.01 G) during aircraft parabolic flight; (C) Effects of gravity on the surface temperature of plant reproductive organs.

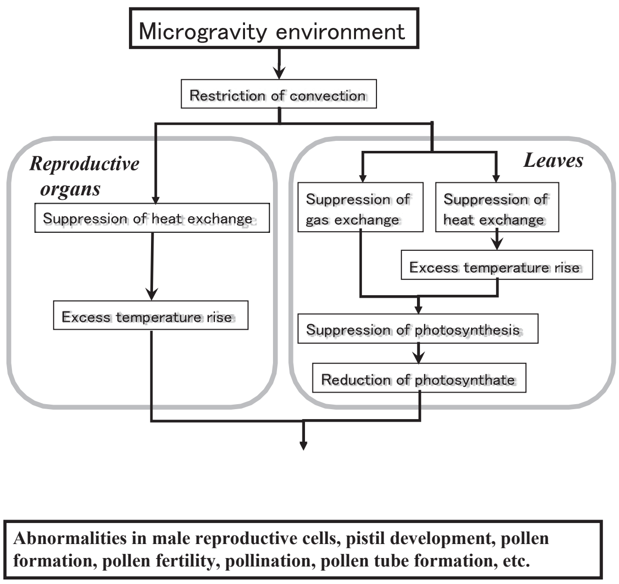

Fig. 4.6 Possible effects of microgravity on plant reproductive growth from the perspective of gas and heat exchanges.

4.3 Other issues regarding plant cultivation in the space environment

Because the lunar surface is almost a vacuum at 0 atm, and the surface of Mars is 0.06 to 0.09 atm, it is easy to reduce the pressure inside the space station partially. Under such low-pressure conditions, the structure of the facility's outer wall can be simplified by reducing the pressure inside the facility. Therefore, during plant cultivation in space, the establishment of plant cultivation technology in a low-pressure environment is also an important issue. It has been reported that spinach and similar plants grow normally in cultivation under a low pressure of 1/4 of the atmospheric pressure [11)]. In addition to low pressure, microgravity is also advantageous in reducing the weight of the facility's load-bearing structure.

In a closed environment, various trace levels of harmful gases can be generated and accumulated. In particular, ethylene is an important plant growth regulator, and the plant itself is also a source. In general, when the ethylene concentration in the air rises above 0.1 $\mu mol\ mol^{-1}$, the plants are damaged. In a closed environment, it is necessary to monitor the behavior of various trace gas components, and a trace gas removal system is indispensable when problems occur because of excessive accumulation.

Water supply to plant roots under microgravity is also an important issue. On earth, the waterfall phenomenon because of gravity is used in plant cultivation methods in the water supply system. However, in the microgravity environment of space, water falling is restricted. Therefore, it may be necessary to utilize pressure gradients or capillary forces to supply water to the roots.

4.4 Function and structure of the cultivation system

Assuming a vacuum environment on the lunar surface, the building structure in which the cultivation equipment is installed is preferably a pressure-resistant container having a cylindrical shape that can withstand the difference in air pressure between the inside and outside, or a half-cylindrical shape obtained by cutting the cylinder in half. It is conceivable to introduce a hydroponic cultivation system having a multi-layer structure with a pressure-resistant structure container. Multi-layer hydroponic cultivation equipment that uses LEDs as a light source has already been developed in Japan and overseas, and cultivation results have been attained. For example, Photo 4.7 shows the LED multi-layer hydroponic cultivation system developed at Tamagawa University (Watanabe, 2011). It has a structure where many cultivation systems are stacked on a multi-stage cultivation frame by combining a water-cooled LED panel light source with improved durability and a hydroponic system of a thin hydroponic solution method (NFT hydroponic method). By pouring the hydroponic solution into shallow gutters and letting the roots crawl there, it is possible to produce hydroponic equipment that is lighter and thinner than the deep flooded hydroponic solution method (DFT hydroponic method), and which has a multi-layer structure. In this case, it is possible to build many cultivation systems in a limited space, advantageous in terms of space efficiency. Fig. 4.8 shows a vegetable production system in which the cultivation system is stacked in 12 stages (Hagiya & Watanabe, 2015).

Fig. 4.7 Multi-layer nutrient film technique hydroponics system with light emitting diodes (FST laboratory, Tamagawa University).

Fig. 4.8 Twelve-layer leaf lettuce production facility (LED Farm, Tamagawa University)

4.5 Cultivation method, conditions, and management

The cultivation method, conditions, management, and calendar were summarized for the eight crops that are to be cultivated on the lunar farm. The main points are below.

(1) Leaf vegetables with a short cultivation period: leaf lettuce.

The cultivation period is short and can be harvested in approximately 5 weeks. They have a good track record in LED hydroponics.

(2) Cereals with a long cultivation period: rice, soybeans.

It takes approximately 16 weeks to harvest rice and soybean, and long-term cultivation is required. It is appropriate to deploy the cultivation equipment in a plane and replant the entire crop at each harvest.

(3) Root vegetables: sweet potatoes, potatoes.

For root vegetables, the use of mist hydroponics is effective. Currently, both sweet potatoes and potatoes require a cultivation period of approximately 25 weeks, and shortening the cultivation period is an issue. By adopting the hydroponic method, it is possible to harvest from tubers and rhizomes that have reached the harvest time.

(4) Fruit vegetables: strawberries, tomatoes, cucumbers.

For strawberries, research examples have been reported using the LED multi-layer cultivation method. There are few research examples of LED cultivation for tomatoes and cucumbers, but it is possible to adopt a multi-layer cultivation system by arranging the harvested products horizontally on the cultivation panel. Tomatoes are harvested 16 weeks after sowing, and cucumbers are harvested 10 weeks after sowing.

These features, further detailed growth processes, notable monitoring items in each growth stage, and cultivation work according to each crop species are summarized in Japanese version of this report. If you need the details, see the attachment data “Growth characteristics and cultivation calendars by crop species” in Chapter 4 of the Japanese version.

References

1) Kitaya, Y., Shibuya, T., Kozai, T. and Kubota, C. Effects of light intensity and air velocity on air temperature, water vapor pressure and CO_2 concentration inside a plants stand under an artificial lighting condition. Life Support & Biosphere Science, 5, 199-203, 1998.
2) Kitaya, Y., Shibuya, T., Yoshida, M. and Kiyota, M. Effects of air velocity on photosynthesis of plant canopies under elevated CO_2 levels in a plant culture system. Advances in Space Research, 34, 1466-1469, 2004.
3) Kitaya, Y., Kiyota, M., Imanaka, T., and Aiga, I. Growth of vegetables suspended upside down. Acta Horticulturae, 303, 79-84, 1992.
4) Merkies, A.I. and Laurinavichyus R.S. Complete cycle of individual development of Arabidopsis Thaliana Haynh plants at Salyut orbital station. Doklady AN SSSR 271, 509-512, 1983.
5) Mashinsky, A.L., Ivanova I., Derendyaeva T., Nechitailo G.S. and Salisbury F.B. From seed-to-seed experiment with wheat plants under space-flight conditions. Adv. Space Res. 14, 13-19, 1994.6) Salisbury, F.B., Bingham G.E., Campbell W.F., Carman J.G., Bubenheim D.L., Yendler B. and Jahns G. Growing super-dwarf wheat in Svet on Mir. Life Support and Biosphere Science, 2, 31-39, 1955.
7) Kitaya, Y., Kawai M., Tsuruyama, J., Takahashi, H., Tani, A., Goto, E., Saito, T. and M. Kiyota. The effects of gravity on surface temperatures of plant leaves. Plant, Cell & Environment, 26: 497-503, 2003.
8) Kitaya, Y., Kawai M., Takahashi, H., Tani, A., Goto, E., Saito, T., Shibuya, T. and Kiyota, M. Heat and gas exchanges between plants and atmosphere under microgravity conditions. Annals of the New York Academy of Sciences, 1077, 244-255, 2006.
9) Kitaya, Y., Kawai M., Tsuruyama, J., Takahashi, H., Tani, A., Goto, E., Saito, T. and M. Kiyota. The effect of gravity on surface temperature and net photosynthetic rate of plant leaves. Advances in Space Research 28, 659-664, 2001.
10) Hirai, H. and Kitaya, Y. Effects of Gravity on Transpiration of Plant Leaves. Annals of the New York Academy of Sciences, 1161, 166-172, 2009.
11) Goto, E., Iwabuchi, K. and Takakura, T. Effect of reduced total air pressure on spinach growth. Agricultural and Forest Meteorology, 51(2): 139-143, 1995.
12) Watanabe, H., Light-controlled plant cultivation system in Japanese – Development of a vegetable factory using LEDs as a lighting source for plants. Acta Horticlturae 907, 37-44, 2011.
13) Hagiya, K. and Watanabe, H. Sci Tech Farm Co., Ltd. in Japan. in Plant Factory: An indoor vertical farming system for efficient quality food production, eds. Kozai, T., Nui, G. and Takagi, M., 55-59, 2015.

5. HIGH-EFFICIENCY FOOD PRODUCTION

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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.

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)].

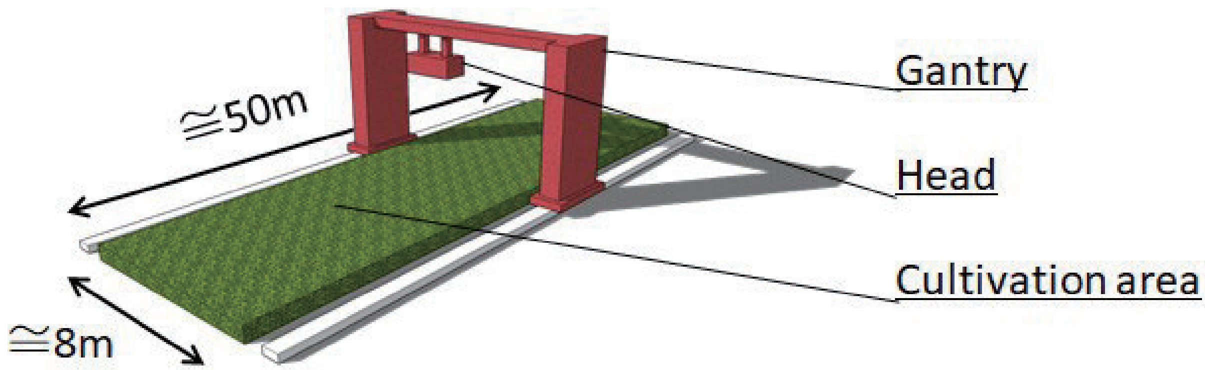
The table below summarizes the work and sensing items necessary from sowing or planting to harvesting for the eight crops that are expected to be produced, and judgment was added as to whether existing technologies can be applied or new technology development is required to achieve them.

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)



B)

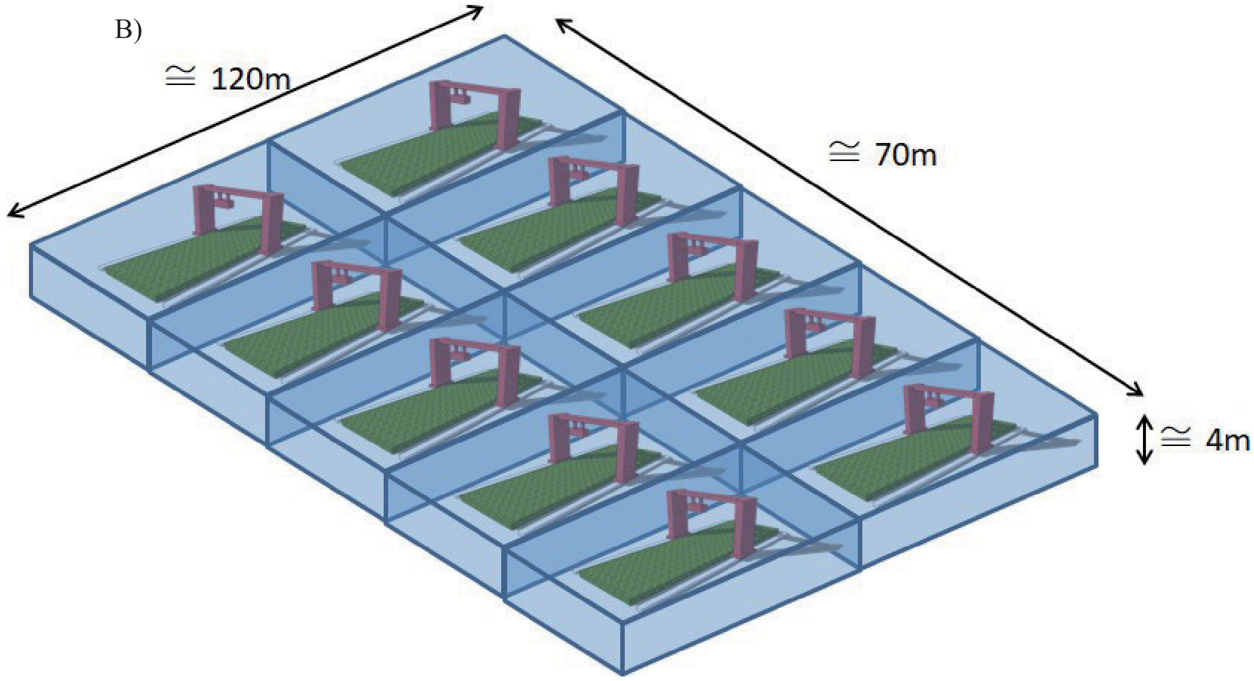


Fig. 5.1 Gantry type cultivation used in batch systems

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	

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.

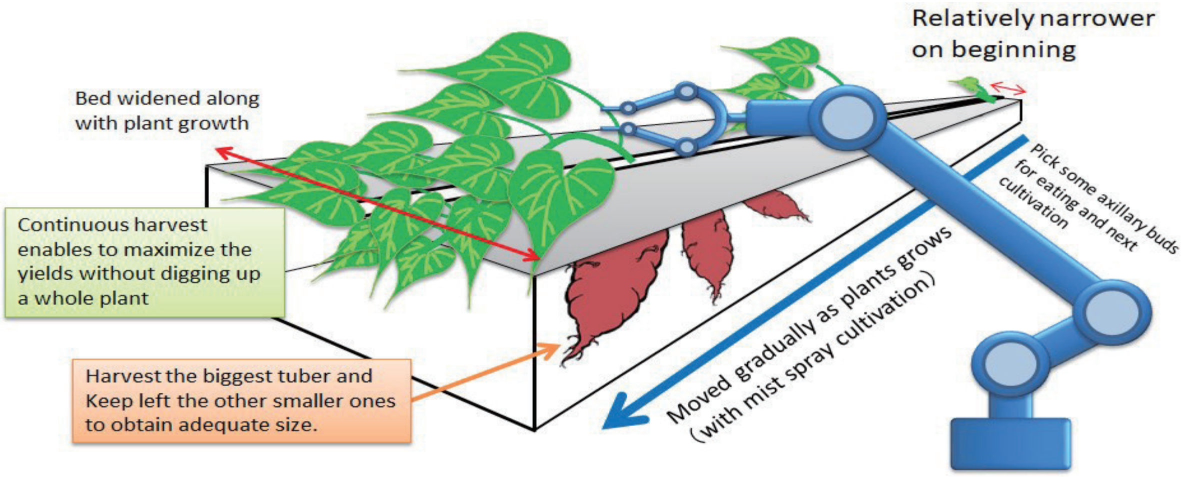


Fig. 5.2. Schematic diagram of a continuous cultivation system that expands cultivation range along with sweet potato leaf abundance

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).

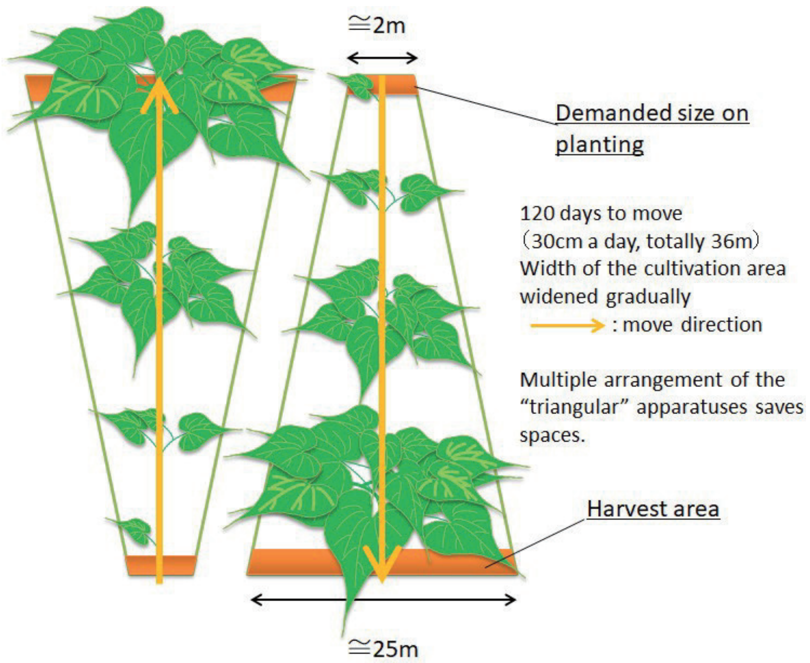
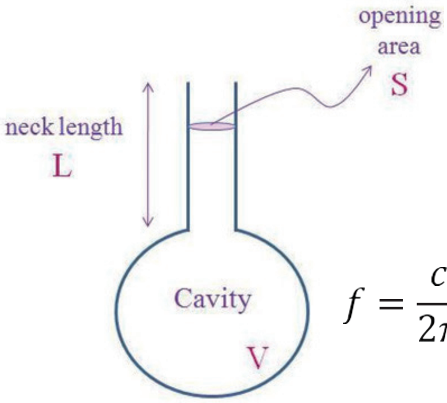


Fig. 5.3. Increase in the efficiency of the area used by inter-strain expansion in continuous cultivation

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 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.

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).

A) B)

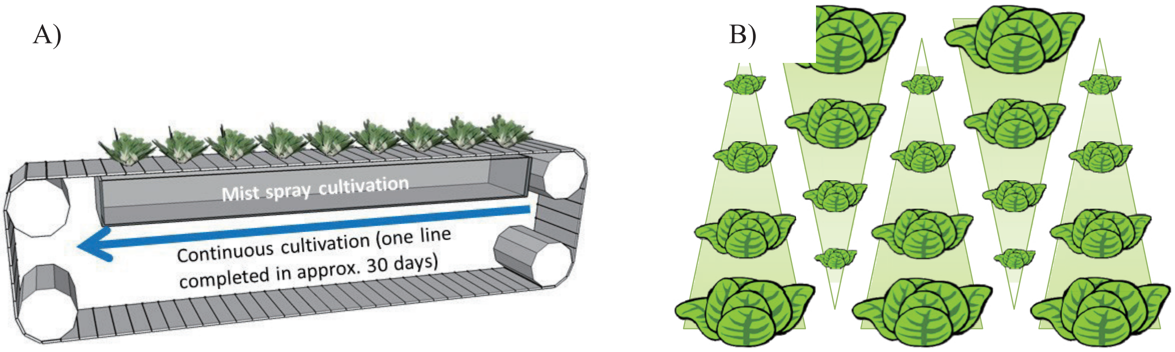


Fig. 5.5. Image of continuous cultivation method of lettuce

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.

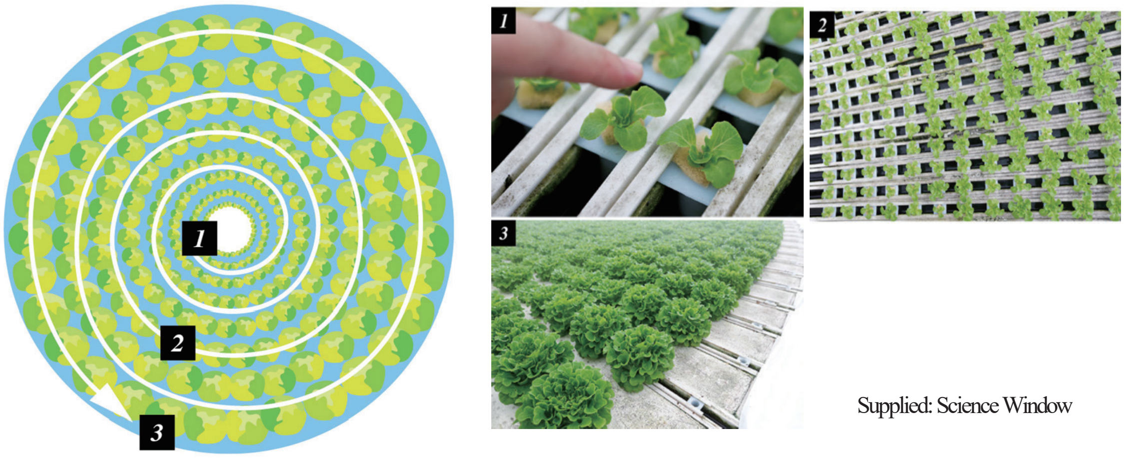


Fig. 5.6 Schematic diagram of the cultivation method that moves spirally from the center to the outer circumference and the actual inter-strain adjustment method

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.

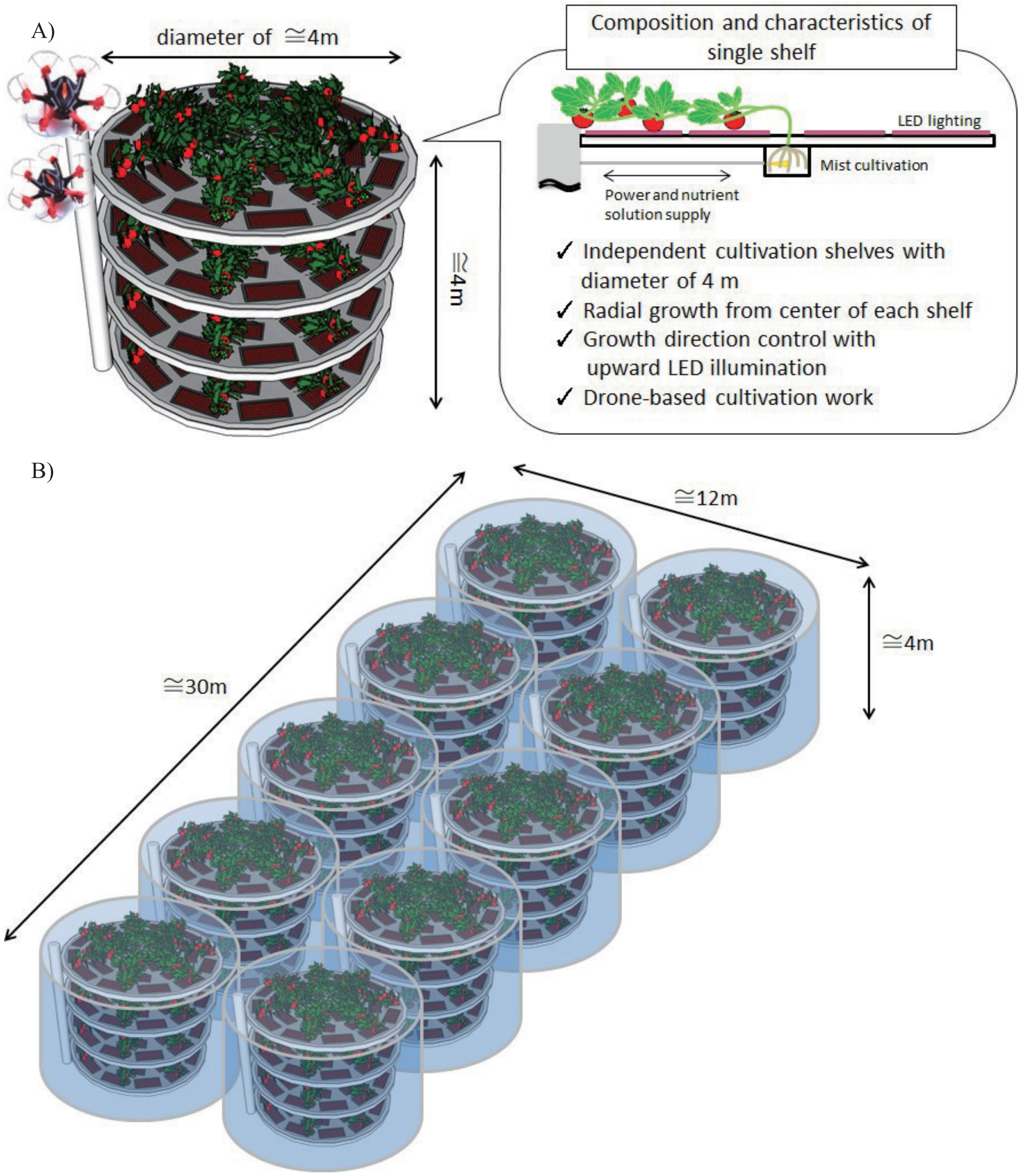


Fig. 5.7 Image of multi-level shelves for tomato cultivation
A) Image and size when the unit module is a set of four stages
B) Proposed system for supplying 100 residents

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 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 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.

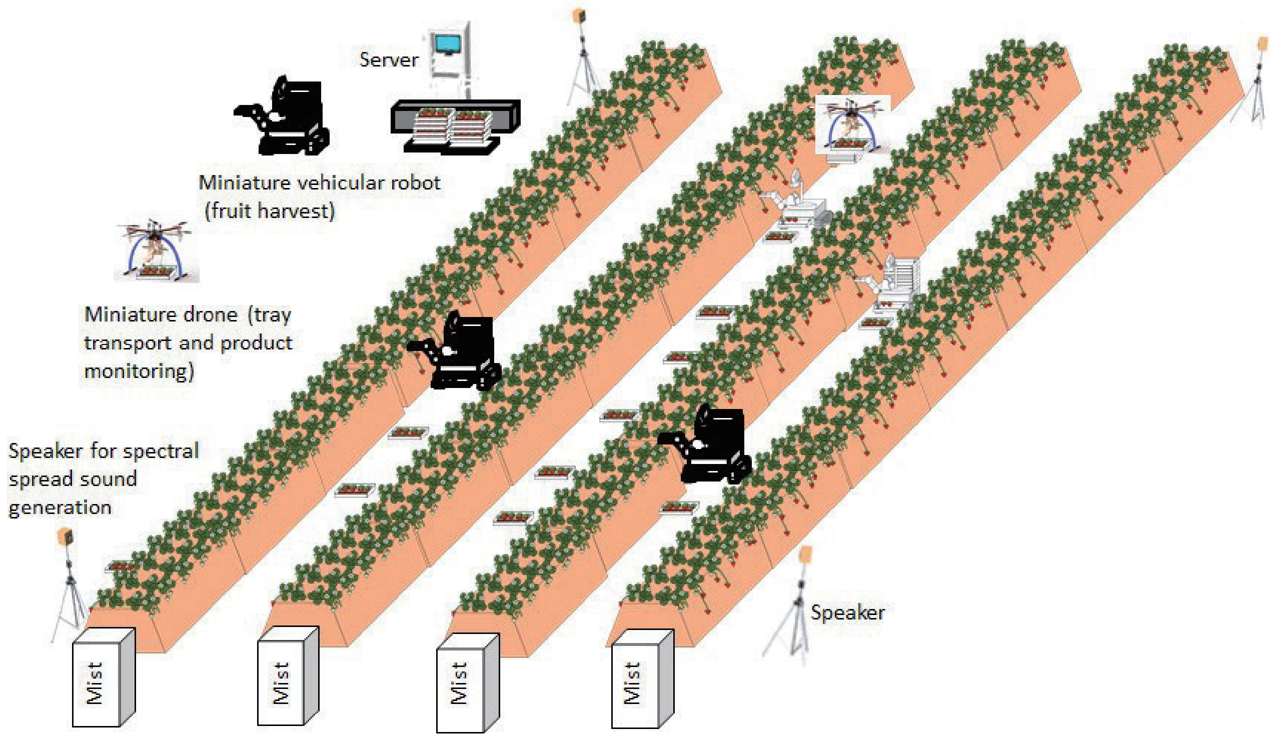
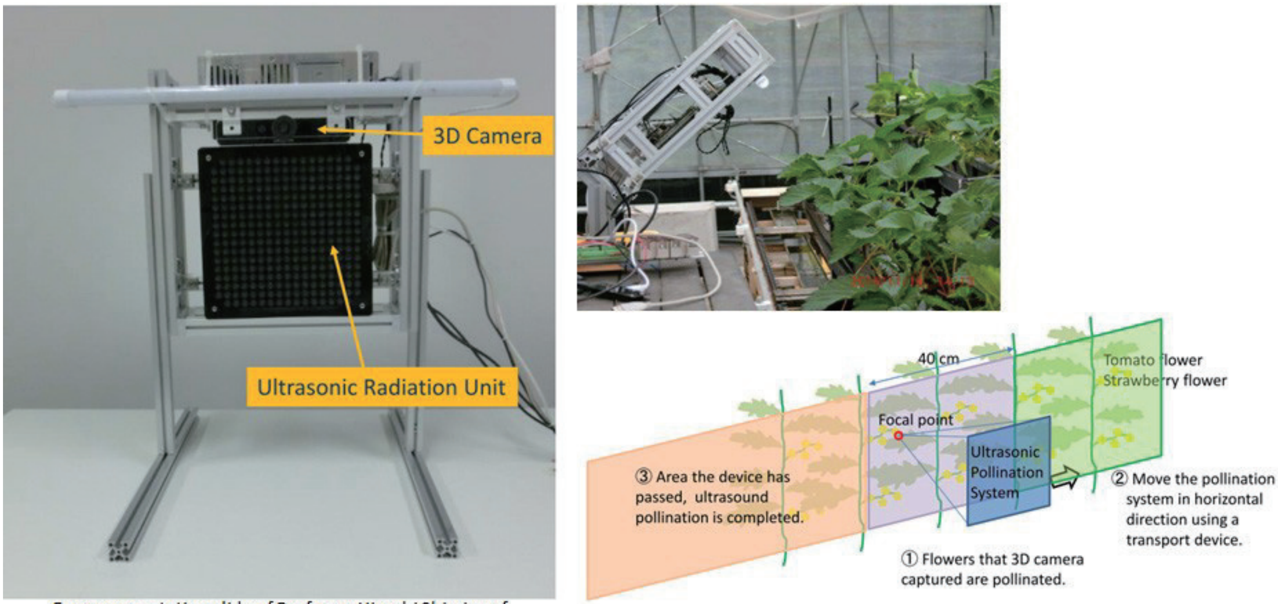


Fig. 5.8 Schematic diagram of multiple drones and harvesting robots controlled by the strawberry cultivation method and spectral diffusion sound signal

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.



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

References

1) Patent JP-A-2009-055871 Spray hydroponics method.
2) Takayama et al., Sensing in a plant factory, Closed Ecosystem and Ecological Engineering Handbook (2015), 367-371
3) K. He, X. Zhang, S. Ren, and J. Sun, "Deep residual learning for image recognition," in IEEE Conference on Computer Vision and Pattern Recognition (CVPR), 2016, 770–778.
4) Duckett, T., Pearson, S., Blackmore, S., Grieve, B. and Smith, M. (2018) White paper - Agricultural Robotics: The Future of Robotic Agriculture.
5) Maruyama et al., Control of Culture Environment and Cleaning Techniques for Closed Plant Factory with Artificial Lighting, Aerosol Research 2016, 31 (2), 104-109.
6) Kawano et al., Nondestructive Quality Evaluation of Agricultural products and Food using Near Infrared (NIR) Spectroscopy, Journal of the Japanese Society of Agricultural Machinery 2013, 75 (2), 67-73
7) H. Xu, H. Chen, Y. Ying, N. Kondo, 2015, Fruit Density as an Indicator for Watermelon Hollow Detection Using Helmholtz Resonance, Transactions of the ASABE, 57 (4), 1163-1172.
8) Hamai et al., Cultivation of purple sweet potatoes using plantlets from meristem culture, Journal of the Society tropical resources technologists, 1993, 9 (1), 5-9.
9) JST Science Window 2016 Autumn, pp. 18-19
10) Year-round high-yield production technology manual for tomatoes by low-stage and multi-stage combined cultivation, SHP Kanto Area Agricultural Research and Extension Council, March 2010
11) Naoshi Kondo et al., Development of an End-Effector for a Tomato Cluster Harvesting Robot, Engineering in Agriculture, Environment and Food 2010, 3(1), 20-24,
12) Ogoshi et al., A simple high-bench culture system for gathering of strawberry nursery plant, Tohoku Agricultural Research. 2001, 54, 187-188.
13) Slamet Widodo et al., Moving Object Localization Using Sound-Based Positioning System with Doppler Shift Compensation, Robotics 2013, 2, 36-53
14) H. Shimizu, Development of ultrasonic pollination system, 2018 CIGR

6. SUSTAINABLE MATERIAL CIRCULATION SYSTEM

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Overview

To enable long-term stays on the moon, it is necessary to solve problems such as the treatment of organic waste generated in life on the moon and the lack of resources for plant production. The 3rd Lunar Farm Working Group aimed to build systems necessary to establish a sustainable lunar farm, such as *in-situ* resource utilization (ISRU). We discuss on efficient recycle systems of organic waste on the moon.

Because of the enormous cost of transportation between the Moon and Earth, it is desirable to recover and recycle elements, such as carbon and nitrogen, required to produce crops from organic waste, such as crop residue. The organic wastes generated on the lunar surface are crop residues, such as non-edible parts, wastewater from cultivation, urine, and feces. To circulate these resources efficiently, a field test on the moon is necessary. Treatments using microorganisms, such as methane fermentation, are commonly practiced on the earth; activated sludge method and composting are also effective and considered the cores of resource circulation. This paper summarizes the results of the third group's studies and proposes resource recycling systems for a sustainable lunar farming using lunar minerals (regolith).

6.1 Introduction

The 3rd Lunar Farm Working Group discussed resource recycling systems on lunar farms. As a result, treatments using microorganisms, such as methane fermentation (anaerobic digestion) and the activated sludge method, an aerobic treatment, were assumed to form the core for efficient recycling of organic residues on the lunar surface. Furthermore, considering efficient resource circulation on the lunar surface, we also concluded the importance of flexible use or combined use of the microbial treatment methods according to the properties of residues and the type of cultivation medium. Supplying elements, such as potassium (K), phosphorus (P), calcium (Ca), and magnesium (Mg), which are required for crop cultivation and exist in lunar minerals (moon regolith), would be useful in terms of efficient resource utilization.

6.2 Supply of elements to plants on the lunar surface

To stay on the moon for a long time, recycling, especially the construction of an elemental circulation system, is indispensable. As shown in Table 6.1, for humans to maintain their vital activities, it is necessary to ingest various minerals and sugars as energy sources as well as amino acids and vitamins that the body cannot synthesize by themselves[1)]. Therefore, building a system that can efficiently recycle elements in food residues is the key to support human activities on the lunar surface for a long time. Plants can supply many of the minerals that humans need to survive. Therefore, considering material circulation in cultivation on the lunar surface, nitrogen (N) is most important for crop production in the early stage of lunar settlement and it requires a great deal of labor and energy to collect N on the lunar surface. It will be important to bring a large amount of elements, such as nitrogen (N), sulfur (S), potassium (K), phosphorus (P), carbon (C), hydrogen (H), and oxygen (O), from the Earth.

Table 6.1 Elements that make up plants and animals

		※	Element name	Element symbol	Element no.	Essential for plants	Essential for humans	Essential for mammals	Chemical properties	Concentraion in the Earth's crust (%)	Concentration in seawater g/L, (g/kg*)		Concentration in angiosperm 2) mg/kg	Amounts present in adult human body (weight: 70 kg)	Active in-body substances that contain the element	Symptoms of deficiency in humans
			Carbon	C	6	○	○	○	Non-metal	0.02	0.026	*	454000	12.6 kg	Proteins, nucleic acids, lipids, etc.	
			Hydrogen	H	1	○	○	○	Non-metal	0.14	-		55000	7 kg	Proteins, nucleic acids, lipids, etc.	
			Oxygen	O	8	○	○	○	Non-metal	46.6	0.0024	*	410000	45.5 kg	Proteins, nucleic acids, lipids, etc.	Malnutririon
			Nitrogen	N	7	○	○	○	Non-metal	0.002	0.0083	*	30000	2.1 kg	Proteins, nucleic acids, etc.	
Major minerals		◎	Calcium	Ca	20	○	○	○	Metal, light metal	3.39	0.41		18000	1.05 kg	Hydroxyapatite	Osteoporosis
		○	Phosphorus	P	15	○	○	○	Non-metal	0.08	0.0006		2300	0.7 kg	Hydroxyapatite	Bone disease
		◎	Potassium	K	19	○	○	○	Metal, light metal	2.4	0.38		14000	140 g		Asthenia, arrhythmia
			Sulfer	S	16	○	○	○	Non-metal	0.06	0.905		3400	175 g	Amino acids, glutathione	
			Chlorine	Cl	17	○	○	○	Non-metal	0.19	18.8		2000	105 g	Gastric acids	
		○	Sodium	Na	11		○	○	Metal, light metal	2.63	10.77		1200	105 g		Muscle pain, heat cramps
		◎	Magnesium	Mg	12	○	○	○	Metal, light metal	1.93	1.29		3200	105 g	MG-bound ATP	Heart disease
Trace minerals	I	◎	Iron	Fe	26	○	○	○	Metal, heavy metal	4.7	0.00002		140	6 g	Hemoglobin, enzymes	Iron deficiency anemia
		◎	Zinc	Zn	30	○	○	○	Metal, heavy metal	0.004	0.000049		160	2 g	Enzymes	Hair loss, skin diseases
		◎	Copper	Cu	29	○	○	○	Metal, heavy metal	0.01	0.0000003		14	80 mg	Enzymes	Anemia
		○	Manganese	Mn	25	○	○	○	Metal, heavy metal	0.09	0.000002		630	100 mg	Enzymes	Bone lesions
		○	Iodine	I	53		○	○	Non-metal	0.00003	0.0005			11 mg	hyroid hormone	Goiter
		○	Selenium	Se	34		○	○	Non-metal	0.00001	0.000002			12 mg	Enzymes	Heart disease, Keshan disease
			Molybdenum	Mo	42	○	○	○	Metal, heavy metal	0.0013	0.0001		0.9	10 mg	Enzymes	
			Cobalt	Co	27		○	○	Metal, heavy metal	0.004	0.0000005			1.5 mg	Vitamin B12	Pernicious anemia
			Chromium	Cr	24		○	○	Metal, heavy metal	0.02	0.000003			2 mg	GTF	Glucose intolerance
	II		Fluorine	F	9			○	Non-metal	0.03	0.013			3 g		
			Silicon	Si	14			○	Metalloid	25.8	0.002		200	2 g		
			Rubidium	Rb	37				Metal, light metal	0.03	0.00012		20	320 mg		
			Bromine	Br	35				Non-metal	0.00025	0.067					
		×	Lead	Pb	82			○	Metal, heavy metal	0.0015	0.0000001		2.7	120 mg		
			Aluminum	Al	13				Metal, light metal	7.56	0.00002		550	60 mg		
		×	Cadmium	Cd	48				Metal, heavy metal	0.00005	5.00E-09			50 mg	Enzymes	
		×	Boron	B	5	○			Metalloid	0.001	0.0044		50			
			Vanadium	V	23			○	Metal, heavy metal	0.015	0.000025		1.6	1.5 mg	Enzymes	
		×	Ardenic	As	33			○	Metalloid	0.0004	0.000037			2 mg		
			Nickel	Ni	28	○		○	Metal, heavy metal	0.01	0.000017		2.7	10 mg	Enzymes	
		×	Tin	Sn	50			○	Metal, heavy metal	0.004	0.0000001			20 mg		
			Lithium	Li	3				Metal, light metal	0.006	0.00018					
			Strontium	Sr	38			○	Metal, light metal	0.0375	0.0078	*	26	320 mg		

Editor: Yoshinori Itokawa, Mineral Encyclopedia 2003 Edition (excerpts, modified)
1) Editor: Yoshinori Itokawa, Mineral Encyclopedia 2003 Edition (excerpts, modified)
2) Eiichi Takahashi, Comparative Plant Ecology, 1974

Note: Lists nutrients that are essential for human life activities and for which the scientific basis is widely recognized and established in medical and nutritional science. ◎:Minerals for which specification standards have been established, ○: Other minerals, ×: Toxic elements in foods with specification standards

6.3 A proposal to closure of material-use loop system for crop production in lunar surface

6.3.1 Presumed resource circulation system

Biochemical material conversion using microorganisms was assumed as the core processing technology of the resource recycling system on the lunar farm (Fig. 6.1). On the moon, there is little N, carbon (C), and water. Because these elements are also essential to plants, they need to be efficiently reused as resources. Therefore, efficient resource circulation must be achieved by separating the areas where humans live, plants are produced and waste is treated, and by bridging wastes and products. Additionally, because the initial stage of lunar settlement has to rely on food transported from the Earth, excreted urine and feces should be efficiently stocked in the waste treatment area as fertilizer resources for future resource circulation. On the other hand, biochemical conversion of organic waste by microorganisms has been established on the Earth as waste treatment technologies, but the risk of environmental pollution by microorganisms will be an issue in closed spaces, such as lunar farms. Indigenous bacteria inhabit humans and plants and thus it is difficult to eliminate bacteria and viruses completely. To establish a sustainable crop production system and prepare for the risk of the spread of phytopathogens, it is important to establish beneficial microbial flora on the lunar farm.

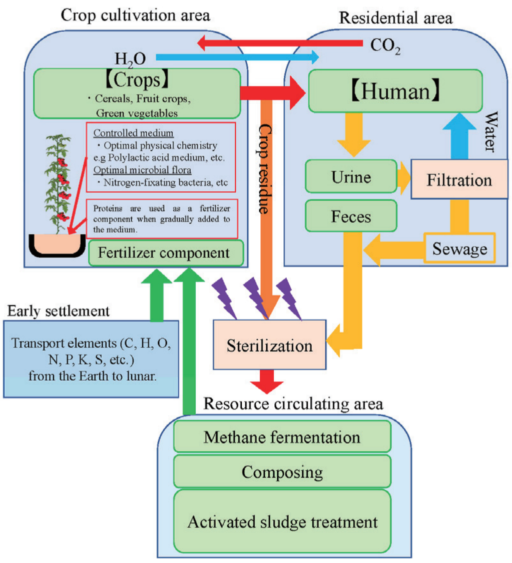

Fig. 6.1 Image of food production and resource recycling system on the lunar farm

Risks, such as crop diseases, are lowered by dividing each cropping area. By introducing sterilization technology with ultraviolet sterilization and membrane filtration, we should establish technology to convert organic waste into resources through methane fermentation and composting.

6.3.2 Use and control of microorganisms

The area of farmland required for food supply to live on the moon was calculated by Group 4 (Table 6.2). The third group showed methods that might solve the problems when implementing resource recycling and the operation of the production system, based on the assumed scale of agricultural land.

Assuming efficient resource recycling, it is essential to take preventative measures when using microorganisms. If pathogens are not brought with plants from the Earth, crops are safely produced. However, even if sterilization is performed, it is impossible to completely eliminate microorganisms attached to plants, materials, and humans. Because microorganisms can easily propagate in the presence of water, inorganic components, and organic substances, microflora will be formed quickly, even if the cultivation environment is started under sterile conditions. It may be possible to control microflora by inoculating specific microorganisms. It is important to artificially establish microflora resistant to pathogens for a sustainable lunar farming, assuming that pathogen invasion will occur in the near future. This way of thinking is a technique that is also practiced in organic farming on the Earth. Pathogens are reduced by solar heat disinfection and other methods, and composting is also known to kill pathogens and seeds of weeds with heat.

Table 6.2. Calculation examples for required cultivation area (see Table 3.5 in Chapter 3)

	Amount required per person	Productivity in the Plant Factory			Area required per person	Area required	
		Production per crop	Days for cultivation	Daily production		For 6 people	For 100 people
	(g/day)	(g/m^2)	(day)	($g/m^2/day$)	(m^2)	(m^2)	(m^2)
Rice	400	900	90	10	40.0	240	4000
Potato	75	8000	360	22	3.4	20	338
Sweet potato[1)]	150	–	–	20	7.5	45	750
Soybeans	350	1400	100	14	25.0	150	2500
Lettuce	150	2500	30	83	1.8	11	180
Tomatoes	200	83000	360	231	0.9	5	87
Cucumbers	100	70000	360	194	0.5	3	51
Strawberries	50	17000	360	47	1.1	6	106

[1)] Since there are not enough examples of sweet potato cultivation, the daily production is assumed to be about 90% of that of potatoes.

6.3.3 Circulating use of culture solution

Water is also a valuable resource on the moon, and recycling is essential. When reusing water, there is a risk of microbial contamination. However, most microorganisms are harmless, and only a few are particularly harmful to humans. If microorganisms do not damage humans and crops, there is no need for sterilization treatment. Sterilization treatment, however, is indispensable because it is necessary to reduce risks of contamination with pathogenic microorganisms. Currently, water sterilization techniques used on the Earth include sterilization with chlorine and ultraviolet rays and sterilization by filtration; however, chlorine can harm plant roots and human health depending on its concentration. Sterilization by ultraviolet rays or filtration was recommended as methods suitable for lunar farms. In addition to contamination with pathogenic microorganisms, water used for cultivation may contain self-poisoning substances secreted by plants and should be viewed as a potential risk when reusing water. However, contaminants are removed by heat decomposition and filtration with activated carbon.

6.4 Substance conversion using microorganisms

Crop residues, such as non-edible parts, are valuable carbon and nitrogen sources on the moon, and as such, they need to be efficiently reused. Biochemical material conversion using microorganisms will be the core processing technology for efficient recycling of resources on lunar farms (Fig. 6.2). A resource recycling method that does not use microorganisms is in the Closed Ecology Experimental Facilities (CEEF) in Rokkasho Village, Aomori Prefecture. Wet oxidation treatment is used to decompose organic waste in water physically and chemically under high temperature and pressure (see section 6.6). While this abiotic method has the advantage that the time required for decomposition is short, it has the disadvantage of producing gasified nitrogen, which cannot be used as a plant nutrient, and there is a risk of fire because of the high-pressure treatment. On the other hand, biochemical substance conversion, which biodegrades organic waste using microorganisms, has been practiced on the Earth as a common waste treatment technology. In an enclosed space, there is a risk of environmental pollution by microorganisms. Considering the entire lunar farm, diverse bacteria inhabit humans and plants and it is difficult to remove bacteria and viruses even if sterilization is conducted. Thus, to prepare for the risk of phytopathogen invasion, it is important to introduce a stable microbial flora composed of useful microorganisms which are suppressive to phytopathogens. In microbial treatment, the form of fertilizer components differs depending on the type of waste and treatment method. When considering efficient resource recycling on the lunar surface, flexible use or combined used of different microbial treatment methods will be effective according to the properties of residues e and the type of plant culture medium.

At the beginning of lunar settlement, we adopted methane fermentation and composting, together with sterilization technology with ultraviolet sterilization and membrane filtration, in order to convert organic waste into resources. However, if the organic waste contained toxic substances or heavy metals that cannot be biodegraded, they may accumulate in microorganisms, plants, or humans over time and exert adverse effects. Therefore, it is necessary to prepare technologies that selectively eliminate these potential risks.

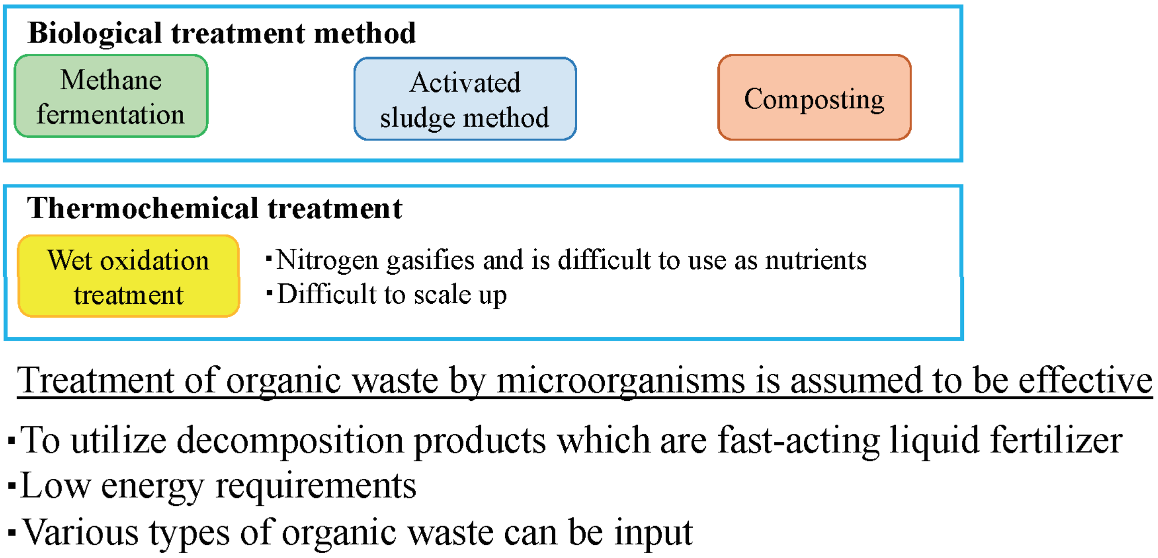

Fig. 6.2 Proposal of a Material Cycle Method Suitable for the Lunar Surface

6.4.1 Methane fermentation

Methane fermentation is a biochemical conversion process of waste biomass conducted by anaerobic microorganisms. Methane fermentation targets waste with a relatively high water content than composting and does not generate much heat during the reaction process. Therefore, the fertilizer components mineralized through methane fermentation are the liquid type. If a high concentration of ammonium in the liquid is oxidized to nitrate, or if a proper application method of ammonium is developed, the liquid can be used as a base for culture solutions used in hydroponic cultivation or as a fast-acting liquid fertilizer (Fig. 6.3). On the other hand, because methane fermentation occurs only in an anaerobic environment with a redox potential of -300 mV or less, complete airtightness of the fermenter is required for high-efficiency treatment.

Methane fermentation is a multi-stage reaction system composed of a wide variety of microorganisms, unlike ethanol fermentation consisting only of yeast. As a result, it is applicable to many types of organic waste . Additionally, many intermediate metabolites, such as organic acids (acetic acid and sulfides), are produced. These are eventually decomposed into methane, ammonia, and carbon dioxide, but it is also possible to intentionally control the process of methane fermentation to extract intermediate metabolites that contribute to human life. For rice and soybeans, the methane fermenter volume were estimated based on the amount of residue generated, the amount of resources produced by methane fermentation using residue obtained at harvest (Tables 6.3 to 6.5). These theoretical values will change depending on various dynamic environmental factors, such as pH, ammonia concentration, the amount of resources recycled, in actual methane fermentation. Moreover, to make a similar trial calculation for other residues, it is necessary to clarify their chemical composition.

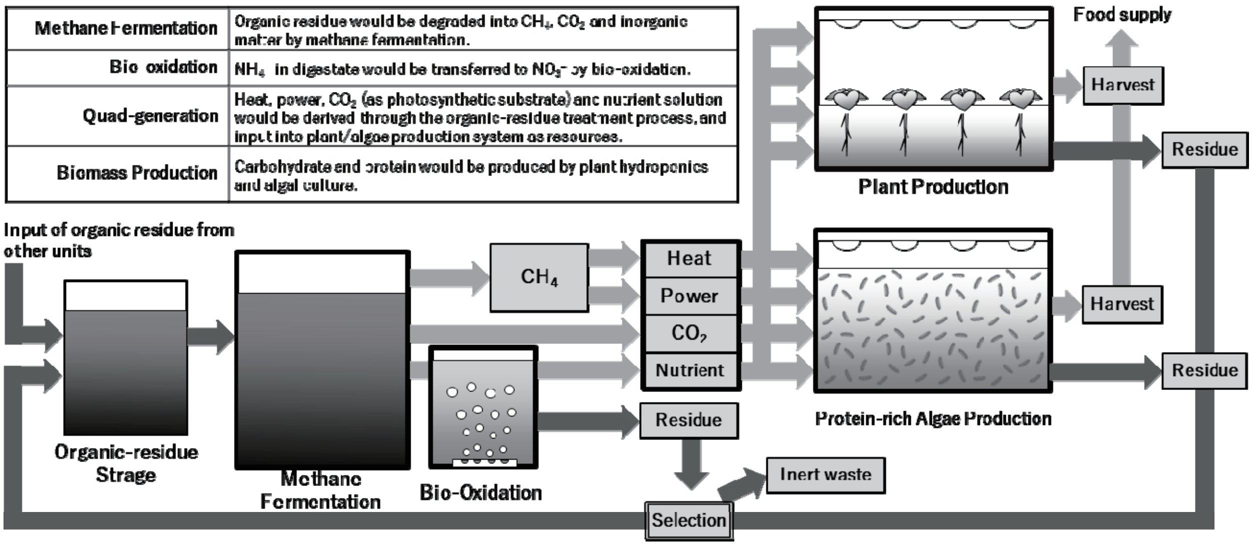

Fig. 6.3 Example of a quad-generation multi-production system for space utilization

Table 6.3 Weight of harvest residue, organic matter content, and moisture content obtained from the required weight of rice and soybeans

	Required weight (g FW d^{-1} $person^{-1}$)	Weight of harvest residue (g FW d^{-1} $person^{-1}$)	Organic matter amount of harvest residue (g VS d^{-1} $person^{-1}$)	Moisture content of harvest residue (g H_2O g FW^{-1})
Rice (refined white rice)	400	–	–	–
Soybeans	350	–	–	–
Rice straw	–	560 [1)]	409 [1)]	0.13 [1)]
Rice husk	–	89 [2)]	63 [2)]	0.09 [2)]
Soybean harvest Residue	–	735 [3)]	632 [3)]	0.14 [3)]
Total	750	1384	1103	–

[1)] Yasui et al.(1969)
[2)] Data from the 2007 Tohoku Biomass Discovery and Utilization Promotion Project (Ministry of Agriculture, Forestry and Fisheries, 2007).
[3)] IPCC report (1996)

Table 6.4 Estimates of CH_4, CO_2, and NH_4^+ production when rice and soybean harvest residues are decomposed by 60% by methane fermentation [1)]

	CH_4 generation (L d^{-1} $person^{-1}$)	CO_2 generation (L d^{-1} $person^{-1}$)	NH_4^+ generation (g d^{-1} $person^{-1}$)
Rice straw	109 [2)]	100	2.0
Rice husk	16 [3)]	16	0.0
Soybean harvest residue	176 [4)]	146	12.9
Total	301	262	14.9

[1)] The report on the methane fermentation decomposition rate of grass from Raku et al. (2005) was applied.
[2)] The C/N ratio was set to 70 by adding the report of Inubushi and Anzai (2001), which set the C/N ratio of rice straw to 60–80; rice straw composition was reported by Yasui et al. (1969), and the composition of rice straw was estimated to be $C_{25}H_{42}O_{20}N_{0.3}$ and calculated using the methane fermentation formula * below.
[3)] Assuming that the rice husks consisted of only carbohydrates, the composition was estimated to be $C_6H_{10}O_5$ and calculated.
4) From the report of the IPCC report (1996), the composition was estimated to be $C_{33}H_{54}O_{24}N_2$ and calculated.
* Methane fermentation formula (Li, 2005):

$$C_nH_XO_YN_Z + \frac{1}{4}(4n - X + 2Y + 7Z)H_2O$$
$$\rightarrow \frac{1}{8}(4n + X - 2Y + 3Z)CH_4 + \frac{1}{8}(4n - X + 2Y - 5Z)CO_2 + Z \cdot NH_4^+ + Z \cdot HCO_3^-$$

Table 6.5. Estimates of total residue volume and methane-fermenter [1)] effective volume by number of residents

Size	One person (Original unit)	Six persons	100 persons
Feed into a methane fermenter L d (person) [2)] of the total volume of the diluent (- [1)] -1 With a [3)] of 20 d of physical residence	6.0 [2)]	36.0	600
Methane fermenter effective volume (L)	120	720	12,000

[1)] The methane-fermentation method used was the continuous operation and wet mesophilic method. The moisture content of the substrates, as well as input loading were assumed to be generally standard conditions (approximately 80% moisture content and 20 d hydraulic residence time) when garbage was used as the substrate.
The water content of 80% was obtained by adding 4,620 g of water, assuming Table 1 where was 1,384 g FW d per person and g H_2O d^{-1} $person^{-1}$ of [2)] water -1 and [2)] water content was 165. The residue after hydration was densified to 1000 g L^{-1}.
The [3)] time-to-residence was determined using the following equation.

$$HRT\ (\text{day}) = \frac{\text{Effective volume of methane fermenter (L)}}{\text{Input of diluted residue (L day}^{-1}\text{)}}$$

6.4.2 Composting and use of residual material

Composting is a relatively simple waste treatment method (Fig. 6.4). The raw materials for compost are mainly coarse organic matter derived from plants, such as rice straw, rice husks, and livestock manure, that can ultimately be decomposed into carbon dioxide and ammonia. Detailed research on composting has been conducted for a long time, including its history [2,3], and many inorganic elements remain in compost. To operate a lunar farm in the long term, it is rational to take advantage of its low energy cost and carbon retention properties and utilize as fertilizers. Additionally, during composting, the compost temperature rises to approximately 60–80°C and a lethal effect on pathogens is expected.

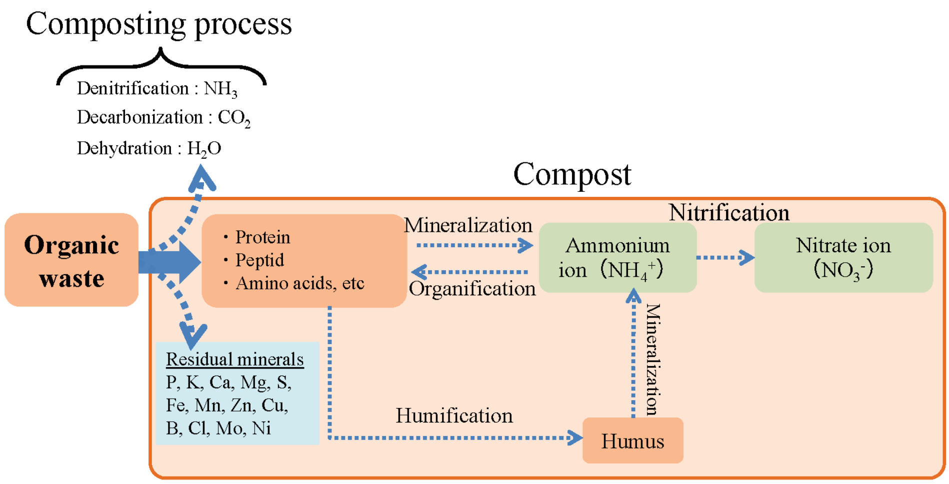

Fig. 6.4 Changes in composted households and nitrogen morphology

6.4.3 Reuse of waste and feces

Resource depletion as fertilizer resources can be avoided by stocking urine and feces excreted daily on the moon in the waste treatment area. Because human excrement contains urea, phosphate, and potassium, a hydroponic cultivation method using human excrement as a raw material has been reported [4]. To efficiently reuse urine and feces, it is necessary to separate and collect urine and feces and process them with a suitable recycling system. When urine is reused as fertilizer, it should be sterilized as necessary and then desalted by filtration or through a dialysis membrane; alternatively, it can be diluted and then used since it has a high nitrogen content. Additionally, urine can be decomposed into ammonium and carbon dioxide by urease and converted into nitrate. The fertilizer effect can be maximized by combining with the fertigation system (Fig. 6.5) [2, 5]. On the other hand, feces can be incorporated into methane fermentation and composting. At this time, CO_2, NH_3, and H_2O can be recovered from the gas phase, and S, Ca, Mg, and trace elements contained in the compost can be reused as resources for crop cultivation. It is desirable to circulate the resources at any time to operate the lunar farm in the long term because feces and urine are valuable elemental resources on the lunar surface.

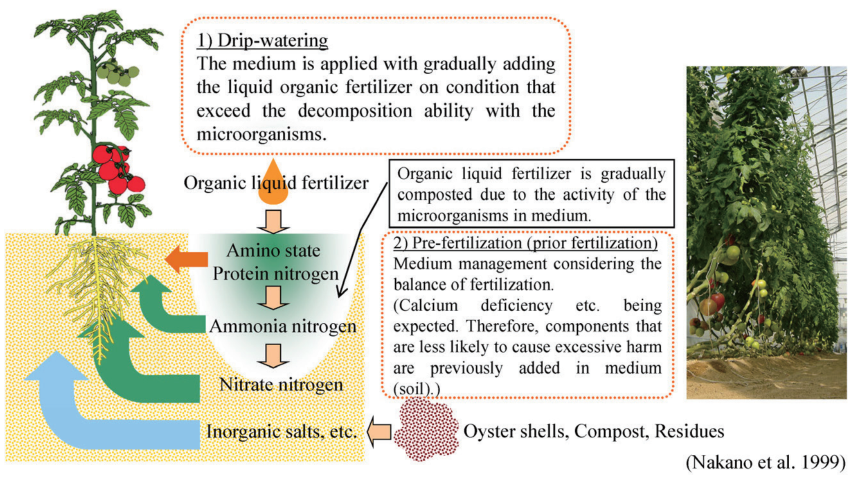

Fig. 6. 5 Fertigation system

6.5 Use of lunar minerals as resources

Since the elements that make up the lunar minerals (lunar regolith) are similar to the soil elements on the Earth [6], in terms of concentrations of Ca, Mg, K, P, and trace elements (Tables 6.6 and 6.7), they can be used as a candidate source of crop nutrients. There are reports of tomato and wheat cultivation using artificial soil created by imitating Mars and the Moon soils[7]. However, the content of heavy metals, such as Mn, Zn, Pb, and Se in lunar regolith is similar to the median values of soil on the Earth, while Ni is six times higher, and Cr is 27 times higher. Additionally, the lunar regolith may contain As, Cd, and Ag, albeit at low concentrations. Assuming that crops will be cultivated using lunar regolith in the future, it is necessary to pay attention to these heavy metals uptaken by crops. Furthermore, it is desirable to elucidate the physical properties of lunar regolith, especially water retention and permeability.

Table 6.6 Example of the rock structure of the Moon (Left)
Table 6.7 Example of rock composition of the Moon and Earth (Right)

		A11	A12	A14	A15	A16	A17	unit
Major and minor elements	SiO_2	42.2	46.3	48.1	46.8	45.0	43.2	(wt.%)
	TiO_2	7.8	3.0	1.7	1.4	0.5	4.2	
	Al_2O_3	13.6	12.9	17.4	14.6	27.3	17.1	
	Cr_2O_3	0.3	0.3	0.2	0.4	0.3	0.3	
	FeO	15.3	15.1	10.4	14.3	5.1	12.2	
	MnO	0.2	0.2	0.1	0.2	0.3	0.2	
	MgO	7.8	9.3	9.4	11.5	5.7	10.7	
	CaO	11.9	10.7	10.7	10.8	15.7	11.8	
	Na_2O	0.5	0.5	0.7	0.4	0.5	0.4	
	K_2O	0.2	0.3	0.6	0.2	0.2	0.1	
	P_2O_5	0.1	0.4	0.5	0.2	0.1	0.1	
	S	0.1	-	-	0.1	0.1	0.1	
Total		99.9	99.6	99.8	100.8	100.8	100.5	

soils & breccias		A11	A12	A14	A15	A16	A17	unit
miscellaneous minor elements	P	560	1616	2073	908	570	453	(μg/g)
	V	69.6	114.4	51.1	110.4	21.1	71	
	Cr	1986	2468	1496	2530	728	2220	
	Mn	1662	1600	1009	1445	511	1252	
	Sr	163	138	184	138	154	153	
Incompatible trace elements	K		540	912	409		440	(μg/g)
	Ba	232	70	146			74	
siderophile elements	Co	31	40.8	34.6	44.6	27	33.8	(μg/g)
	Ni	199	260	411	216	378	211	
vapor-mobilized elements	S	1240	820	870	624	543		(μg/g)
	F			138	69			
	Zn	24.7	6	26.7		19.1		
	As			85				(ng/g)
	Se	330	200	316	193	224		
	Ag					8.5		
	Cd					83		
	Pb	1.61	3.9	8.3	1.81	1.9	1.47	(μg/g)

Oxides	Percentage of lunar rock composition	Percentage of Earth rock composition
SiO_2	44.40%	59.36%
Al_2O_3	6.14%	15.30%
FeO	10.90%	6.43%
MgO	32.70%	3.48%
CaO	2.31%	5.04%
Na_2O	0.09%	3.77%
K_2O	0.01%	3.13%
TiO_2	0.31%	0.33%

Note: Values for Earth rocks are calculated from Clarke numbers.

6.5.1 Water holding capacity of a model lunar regolith

To investigate whether lunar regolith could be used as a nutrient source and a growth medium for growing crops, we examined the water holding capacity of a model lunar regolith provided by JAXA. The results showed that the water holding capacity of the model lunar regolith was lower than that of sand with the lowest water holding capacity in different soils tested (Fig. 6.6A).

Judging from the information on the form of the lunar regolith provided by JAXA, the water holding capacity and physical properties of lunar regolith need to be improved to use as a medium for crop cultivation. Additionally, when we examined several materials that could improve the water holding capacity of regolith, poly (lactic acid) (PLA; a commercial name LACTIF) and paper pulp showed a high water holding capacity (Fig. 6.6B).

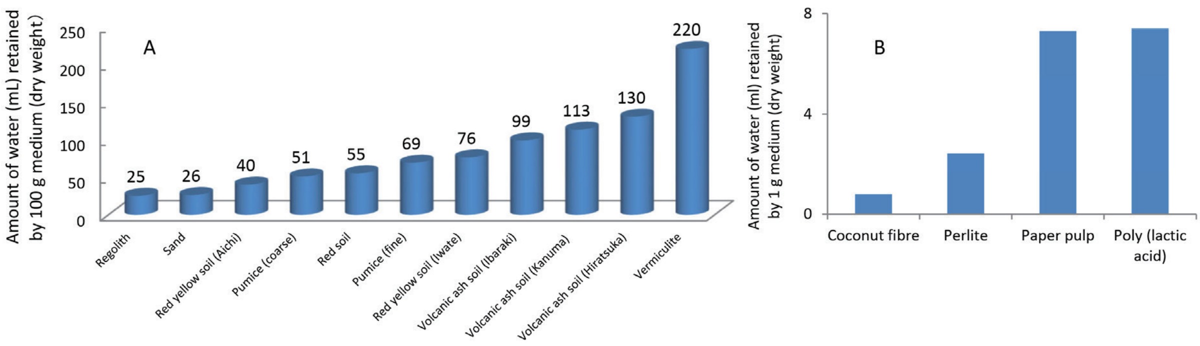

Fig. 6.6 Water-holding capacity of different media and soils

6.5.2 Materials to improve the physical properties of lunar regolith

Physical properties such as water holding capacity need to be improved when lunar regolith is used as a culture medium. One option is to mix with a recyclable material which is light and porous. Poly(lactic acid) (PLA), a biodegradable polymer synthesized from starch or starch-like products, is a candidate (Fig. 6.7). PLA is produced through saccharification of starch, lactic acid fermentation, and polymerization. It is processed into fibers and films [8]. Generally, PLA products are inferior in durability and heat resistance, compared with ABS resin products, but it is possible to give them the same strength as polypropylene, depending on the manufacturing method. Additionally, because it can be ultimately decomposed into water and carbon dioxide by biodegradation, such as hydrolysis and composting, it is a useful material from a perspective of element recycling. Furthermore, when producing crops on a lunar farm, a system of artificial light type plant factories is desirable and it must support growth of seedlings. PLA is biodegradable, but difficult to decompose in compost. Since the yeast *Pseudozyma* and the actinomycete *Amycolatopsis* efficiently decompose PLA[9, 10], it is possible to construct a resource recycling system by inoculating specific microorganisms into the recycling system. Because PLA is synthesized from starch and other raw materials, it can likely be manufactured on the lunar surface by introducing the manufacturing equipment to the lunar farm. A promising material for sustainable operation of the lunar farm is PLA.

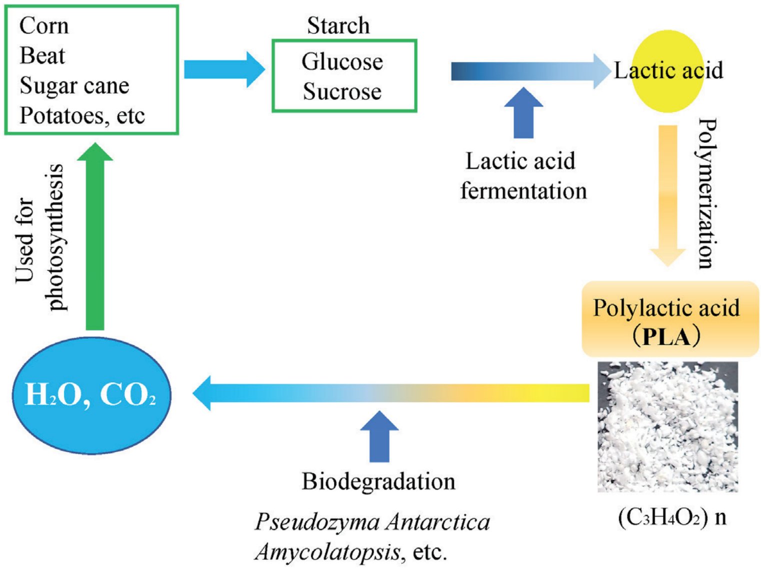

Fig. 6.7 Material cycle of polylactic acid

6.5.3 Crop cultivation test using the model lunar regolith

To determine whether lunar regolith can be used as a local resource after settlement and planting on the lunar surface, soybean, lettuce, and strawberry were grown. The effect of mixing with PLA on their growth was investigated using the LACTIF medium provided by the JSP Corporation.

The results indicated that the model lunar regolith promoted plant growth when used in combination with the LACTIF medium compared with the plant growth in the model lunar regolith only (Fig. 6.8 A, B). The enhanced plant growth may be caused by a higher porosity of the LACTIF medium. Furthermore, when soybean plants were grown in a mixed medium of the model lunar regolith, LACTIF medium and rice straw compost, soybeans were harvested, although slightly smaller than those grown in the control (a culture soil) (Fig. 6.8C).

The results suggested the utility of lunar regolith mixed with a porous material for cultivating crops. Evaluation of the physiological and ecological effects of physical improvement of lunar regolith on crop growth and investigation of harmful heavy metal accumulation in edible parts are needed in parallel with the crop cultivation under the artificial light type plant factory after settlement on the moon if life on the moon stabilizes and settlements consider growing crops using lunar regolith in the future. Thus, to enable long-term residence on the moon, it is important to develop and introduce locally procured materials that can improve the utilization efficiency of recycled resources and the efficient recycling of residues.

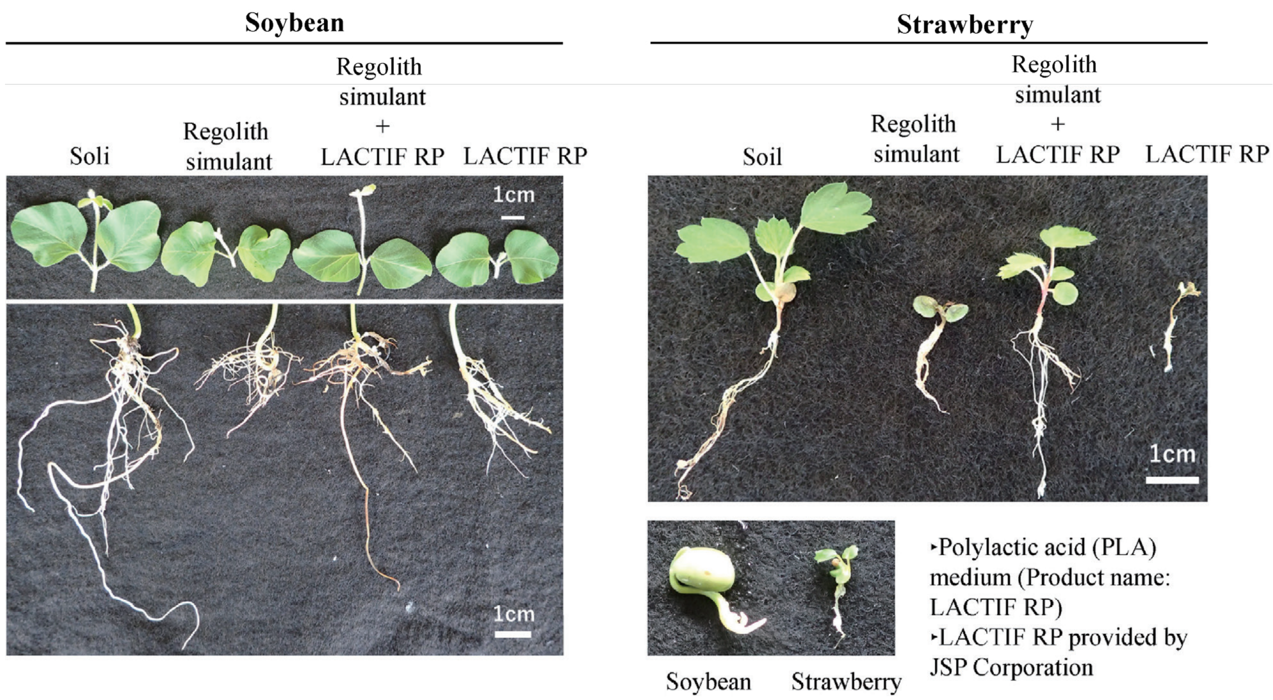

Fig. 6.8. Crops cultivated on each medium

6.5.4 Reuse of regolith

Regolith could be used as a sintered medium, after sterilization with, for example, space radiation. There are not enough actual measurement data of cosmic radiation (mainly proton beams, such as solar particles and galaxy radiation) available in the lunar surface. Thus, it may be more effective to irradiate using an artificially generated ultraviolet lamp. The intensity and time of radiation required for sterilization of regolith will differ depending on the type of target pathogens. It is necessary to study microbial dynamics in the lunar surface.

6.6 Thermochemical processing

At CEEF, a wet oxidation treatment that decomposes human excrement and non-edible parts of crops under high temperature and pressure has been attempted as an abiotic treatment. Wet oxidation is conducted at 374°C or below the critical temperature in a closed high-pressure vessel to prevent water vaporization. The advantages are shorter decomposition time and no microbial contamination in the decomposition products. Consequently, there is less risk of environmental pollution. However, the disadvantages are that it requires a high-pressure treatment and it is difficult to increase the scale. Fig. 6.9 shows a schematic diagram of the wet oxidation treatment, composting, and methane fermentation as resource recycling units.

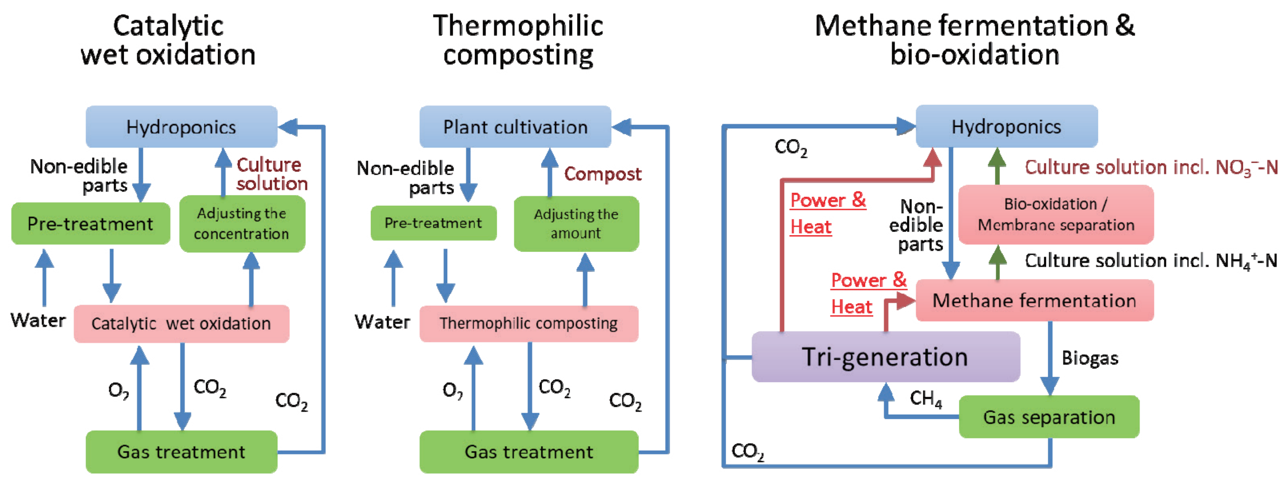

Fig. 6.9 Thermochemical and biochemical treatments for resource-recycling from plant residues in a closed system

6.7 Future prospects of long-term resource circulation on the lunar surface

The primary purpose of using anaerobic fermenters is to produce methane. However, by-products, such as ammonia and sulfide, are generated. These by-products will be important resources that are lacking on the Moon. Therefore, detailed studies on the mechanism and conditions of the anaerobic fermentation process could provide valuable information on efficient resource recycling on lunar farms and efficient methane production on the Earth. Plant cellulose is a primary component in the crop residue. Studies are currently conducted from many perspectives on the efficient decomposition of plant cellulose using fungi and bacteria. Efficient resource recycling will be possible if fungi and bacteria are used to decompose plant cellulose on lunar farms. A future forecast of resource recycling for the sustainable operation of lunar farms is shown in Fig. 6.10.

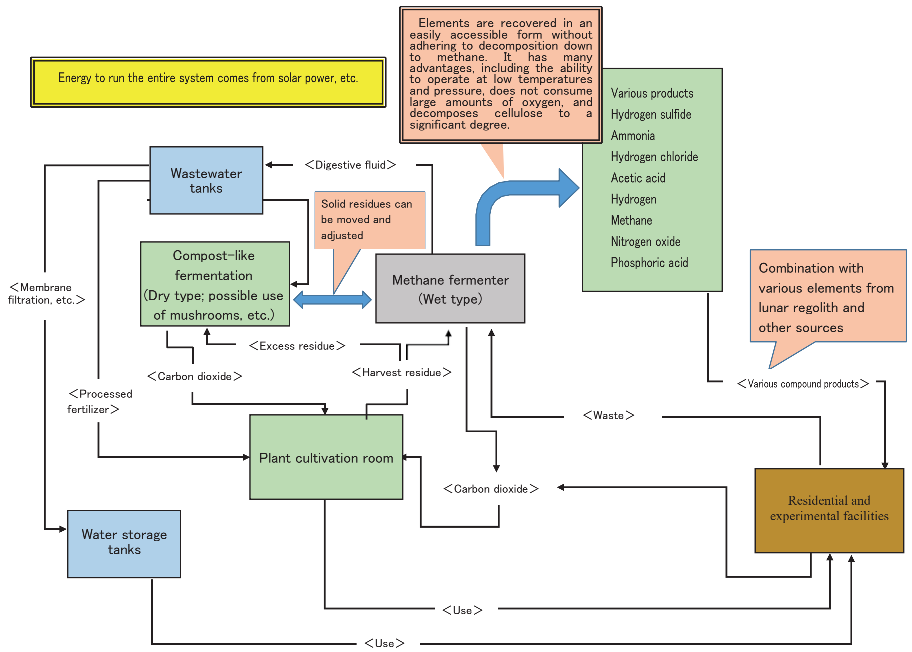

Fig. 6.10 An overview of the material cycle centered on the anaerobic fermenter

With the increasing number of people, it will be necessary to increase the amount of soil with a high buffer function. In particular, since compost, which is one of the base materials of soil, has a high ability to store elements, such as carbon, its need will increase. Additionally, cultivation with a culture medium is also effective at this stage. Cellulose is decomposed by anaerobic fermentation, but it is not highly efficient. Therefore, by introducing composting with high cellulose decomposing ability, the circulation rate of cellulose is effectively controlled by adjusting the input amount to the anaerobic tank and pretreatment. If composting is introduced on the lunar surface, heat produced during fermentation will be obtained and be used for heating a anaerobic fermentation tank or heating a cultivation room. However, because the lunar farm is a completely enclosed space, a device driving composting must utilize the byproducts such as heat and carbon dioxide. Additionally, it may be necessary to introduce PLA, which can be biosynthesized and biodegraded, and pearlite, because their manufacturing from lunar regolith is thought to be possible at an early stage from the time of settlement on the moon. However, if the lunar farm is operated for a long time, inorganic waste will be generated from the living and production space; therefore, it is desirable to establish a recycling system for inorganic waste, such as melting metals and glass in an electric furnace. When constructing a sustainable resource recycling system on the lunar surface, it is important to consider the efficient recycling of all available residues.

Fig. 6.10 targets a circulation system for five people staying on the lunar surface, and it is assumed that the anaerobic fermenter and water tanks function as a buffer, and that the waste will be concentrated in the anaerobic fermenter.

The use of methane as an energy source is not a good option because the energy value is low, and carbon dioxide is easy to use in N and C circulation, assuming high availability of electric energy from solar cells. Ammonium, nitrate, and sulfate are important metabolites in material cycling on the lunar surface. It is necessary to use them in combination with a catalyst-based synthesis method, such as the Haber-Bosch method of ammonia for efficient operation in a closed system.

6.8 Future challenges

We need to bring various supplies, such as microorganisms and crop seeds, to the Moon for material circulation and unintentional contamination by pathogens and disease occurrence will be potential risks. At the beginning of a lunar settlement, crops are mainly cultivated in hydroponic conditions. If a disease occurs, great damage will occur. To control damage to crops, it is necessary to establish measures to prevent the invasion of pathogens, to sterilize the culture system, and to control pathogens with pesticides. On the lunar surface, there exist only microorganisms introduced from the Earth, and thus when pesticides are used for disease control, pesticides may not be decomposed due to the low microbial diversity. Fertilizer utilization efficiency may also be low because of the lack of microbial diversity. It is necessary to discuss the formation of microbial communities that degrade pesticides and stimulate fertilizer use in the material cycle on the lunar surface.

References

1) Ministry of Education, Culture, Sports, Science, and Technology; Food Composition Database.; 2015, https://fooddb.mext.go.jp/index.pl
2) A. Nakano, Integrated Organic Agriculture Theory, Seibundo Shinkosha, 2012.
3) A. Nakano et al., Plants and Facilities Horticultural Handbook, 2015.
4) L. Yang, A. Giannis, V. W.-C. Chang, B. Liu, J. Zhang, J.-Y. Wang. Application of hydroponic systems for the treatment of source-separated human urine, Ecological Engineering, 81, 2015, 182-191.
5) J. Fernandez-Salvador, B.C. Strik, D.R. Bryla, Liquid corn and fish fertilizers are good options for fertigation in blackberry cultivars grown in an organic production system, HortScience, 50(2) 2015, 225-233.
6) SPACE.com, Composition of rocks collected by Apollo 15, 2010.
7) G.W.W. Wamelink, J.Y. Frissel, W.H.J. Krijnen, M.R. Verwoert, P.W. Goedhart. Can plants grow on Mars and the moon: a growth experiment on Mars and moon soil simulants. PLoSONE 9(8), 2014, e103138. https://doi.org/10.1371/journal.pone.01031388
8) Y. Kimura, Producing petrochemical-independent polymers and polylactic acid. Polymers, Polymers, 2015, 64(5), 278-282. http://www.space.com/scienceastronomy/moon-mantle-exposed-craters-100705.html
9) H. Kitamoto et al., Japanese Patent Application No. 2008-023030.(2008)
10) Y. Tokiwa, Microorganisms and Natural Polymers Degrading Biodegradable Plastics, Journal of the Society of Biotechnology of Japan, 2007, 85(6), 264-266.

7. STUDY OF THE LUNAR FARMING SYSTEM

~ Examination of the lunar farm from the viewpoint of life support system design ~

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7.1 Introduction

On the moon, there is a day and night for approximately 2 weeks each in a cycle of approximately 4 weeks, and it is necessary to store electricity at night. Thus, conventionally, food production on the moon has not been an attractive option, and food production has often focused on Mars, which has a day and night cycle of approximately 24 h and 40 min. Since the study in Russia in the 1960s, there have been numerous research examples of crop cultivation for food production in space. Typical examples of simultaneous food production and residence at ground-based experimental facilities include Russia's BIOS [33,4)], the United States' Lunar Mars Life Support Test Project (LMLSTP) [5)], and Japan's Closed Ecology Experiment Facilities (CEEF) [6)]. A recent example is Lunar Palace [17)] in China. Especially in recent crop cultivation, the use of LEDs has become common. It has become possible to design products significantly different in durability, weight reduction, and energy utilization efficiency than when high-pressure sodium lamps were used [8,9,10)].

Therefore, in this study, we will design a lunar farm system that incorporates the latest knowledge of plant factories using the bioregenerative life support system analysis tool [11,12)]. In particular, food production is greatly involved in the design of life support systems, such that the specifications of the entire lunar farm will be examined from the perspective of life support system design. In this report, after presenting the design method and calculation procedure of the analysis tool, an example of designing a lunar farm using set values [13)] examined by the working group is shown.

7.2 Assumptions for the lunar farm design

First, the assumptions for the working group's lunar farm design are shown. The following ground rule and assumptions have been set for the overall system parts required for the lunar base system that other groups are considering.

Ground Rule 1: Six crewmembers live in the lunar outpost where they produce their own food.

Assumption 1: Water, oxygen, and nitrogen can be produced on the moon using ISRU.

Assumption 2: Concrete can be manufactured on the moon.

Assumption 3: Assuming that the base is located in the highlands of Antarctica, solar cells can be used with a sunshine rate of 90%.

Assumption 4: The use of nuclear power is also an option for power sources.

With reference to the nutritional values published in the Japanese Dietary Intake Standards 2015 [14)], cultivated crop candidates were determined to consider the balance of energy, protein, and fat, and the standard model was a 30–49-year-old male (physical activity level II; 2,650 kcal/d). Considering that the nutrition from agricultural products is only plant-derived, animal protein is supplied from Earth. Other deficient nutrients will be supplied from Earth as supplements.

The crop species were selected to consider the cultivation area, energy requirement, labor hours, and the number of cooking menus. Table 7.1 shows the cultivated crops and cultivated amounts currently set by the working group. The required area was determined from the production volume and harvest index obtained at the plant factory on the ground. The eight crop types of rice, potatoes, sweet potatoes, soybeans, lettuce, tomatoes, cucumbers, and strawberries are produced internally. Additionally, the energy and protein that are insufficient for these eight types are calculated on the assumption that 50 g of animal protein will be brought from Earth. Table 7.1 shows the actual floor area considering the energy, required amount, number of days until harvest, harvest index, daily production of edible parts, cultivation area required for food production for one person, and number of cultivation shelves. We consider the three types of rice and soybean cultivation shelves and the floor area shown here.

Table 7.1. Candidate cultivated crops on a lunar farm

Crop	Energy	Required amount*	Days to harvest	Harvest index*	Daily Production*	Cultivated area per capita	Number of cultivated shelves†	Floor area†
	Kcal/d	g/d	d	-	g/m²/d	m²	-	m²
Rice	1421.1	335.2	90	0.5	8.5	40.0	1 2 3	40.0 20.0 13.3
Potato	58.6	15.6	100	0.82	4.6	3.4	3	1.13
Sweet potato	206.2	52.0	120	0.65	7.0	7.5	3	2.5
Soybean	646.9	131.9	100	0.52	5.6	25.0	1 2 3	25.0 12.5 8.33
Lettuce	26.3	7.4	30	0.91	4.2	1.8	5	0.36
Tomato	48.8	12.4	100	0.7	13.9	0.9	1	0.9
Cucumber	18.3	4.8	80	0.7	9.7	0.5	1	0.5
Strawberry	12.2	3.1	60	0.7	2.8	1.1	5	0.22
Subtotal	2438.5	562.4				80.2		70.6 38.1 27.3
Animal protein‡	211.0	50.00						
Total	2649.5	612.4						

* Numbers set at the WG were converted to dry mass
† The number of cultivation shelves for rice and soybeans is examined three ways: one, two, and three. These are called CLOSED 1, CLOSED 2, and CLOSED 3.
‡ Assumes that animal protein was additionally consumed

Based on NASA's advanced life support system standard values [15,16,17], the set values related to human life are shown in Table 7.2.

Table 7.2. Set values related to human life (kg/person/d)

Required items	Lunar base, kg/CM-d
Oxygen	Depending on the settings in Table 7.1
Food (dry)	Depending on the settings in Table 7.1
Food (in water)	Depending on the settings in Table 7.1
Metabolized water	Depending on the settings in Table 7.1
Cooking water	0.76
Drinking water	2.10
Water for handwashing	0.20
Water for showering	2.72
Water for flushing toilet	0.30
Laundry water	12.5
Other	0.78

7.3 Mass balance calculation

Table 7.3 shows the mass balance calculation by biochemical stoichiometry (Appendix 7A) [18, 19] based on the amount of crops cultivated in Table 7.1. The deficient substance becomes the amount supplied from the outside.

Table 7.3. Mass balance model

	Input 1	Input 2	Input 3	Input 4	Output 1	Output 2	Output 3
Plant	CO_2	H_2O	NH_3	HNO_3	Edible	Inedible	O_2
Dry g/CM	1741.2	621.7	19.1	42.4	562.4	497.8	1364.2

Calculations are based on Equations (A1) and (A2) in Appendix 7A

	Input 1–4	Input 5	Output 1	Output 2	Output 3	Output 4	Output 5
Human	Food	O_2	Urine	Feces	Other	CO_2	H_2O
Dry g/CM	612.4	599.0	51.7	105.2	0.00	778.7	275.9

Calculations are performed using the equation (A3) in Appendix 7A

	Input 1–4 or Input 1	Input 2 or Input 5	Output 1	Output 2	Output 3	Output 4
Waste processing	Waste	O_2	CO_2	H_2O	N_2	Residues
Urine, dry-g/CM	43.9	39.0	42.9	26.3	13.7	6.6
Feces, dry-g/CM	105.2	208.7	228.4	76.8	8.7	0.0
Inedible, dry-g/CM	497.8	602.1	789.6	301.5	8.9	0.0
Total, dry-g/CM	646.9	849.8	1060.9	404.6	31.2	6.6

Calculations are based on Equations (A4), (A5), and (A7) in Appendix 7A

	Input 1	Input 2	Output 1	Output 2
N_2 fixed	N_2	H_2O	NH_3	HNO_3
Total, dry-g/CM	25.1	36.4	19.1	42.4

Calculations are based on Equation (A8) in Appendix 7A

7.4 Design of life support system

Using the Equivalent System Mass (ESM) [20] shown in Appendix 7B, we will compare life support systems incorporating lunar farms. ESM consist of mass, volume, power, cooling, and working hours. Based on the life support system element technology candidates [20,21] in Table 7C1 of Appendix 7C, values proportional to the number of people are used. The replenishment mass varies depending on the technology used.

7.4.1 Procedure for calculation

The calculation procedure of the design tool is shown in Fig. 7.1. The procedure of the mission requirement setting, cultivated crop setting, mass balance calculation, subsystem technology setting, and ESM calculation were examined. There are two loops [cultivated crop change and element technology change (B)], and methods for reducing ESM were examined. Additionally, if the cultivated crop data and technical data are updated during the study, the data can be reflected in the overall calculation (A).

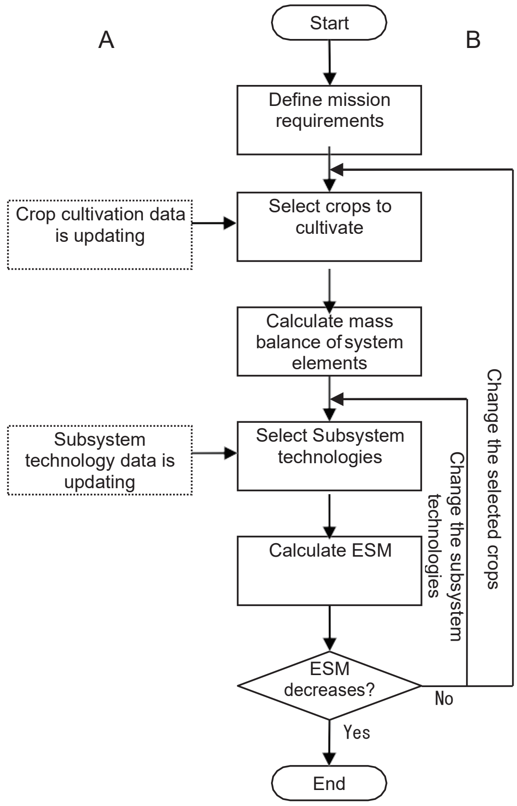

Fig. 7.1 Calculation Procedures for Design Tools

7.4.2 Configuration of the life support system

Table 7.4 shows the elemental technologies of open system, ISS system, and closed system. The combination of mass, volume, power, cooling, and working hours of these three types of subsystems is shown in Table 7C2 of Appendix 7C. The open system does not regenerate the substance after use. The ISS system regenerates carbon dioxide and water and dries and stores waste without regenerating it. The closed system uses plant photosynthesis to regenerate carbon dioxide and water. Waste is processed and reused.

Table 7.4 Subsystem technologies for the lunar base

Subsystem	Subfunction	Open system	ISS system	Closed system
Air revitalization	Carbon Dioxide Removal (CDRA)	LiOH	4BMS	4BMS
	Carbon Dioxide Reduction System (CRS)	-	Sabatier	Crop cultivation
	Trace Contaminant Control System (TCCS)	Activated carbon and air filter	Activated charcoal and air filters	Activated charcoal and air filters
	O_2/N_2 Storage	High pressure	High pressure	Cryogenic
	Oxygen Generation	-	Electrolysis	Photosynthesis
	Temperature and humidity control	CHX	CHX	CHX
Water recycling	Water Storage	Storage	Storage	Storage
	Water Recovery System (WRS)	-	ISS WRS (MF, VRA, PS, and IEB)	Photosynthesis/VPCAR
	Waste Water	Discharge	Storage	Storage

	Collection System			
Waste process	Urine Process	To wastewater tank	VCD	Bioreactor
	Feces processing	Feces bag	Feces bag, Compactor	Bioreactor/wet oxidation
Biomass production	Biomass production	-	-	Crop cultivation
Food storage	Food supply	ISS Food	ISS Food	Supplements, Refrigerator, and Freezer
Accommodations	Laundry	-	-	Washing machine

4BMS: 4 Bed. Molecular Sieve, CHX: Condensing Heat Exchanger, IEB: Ion Exchange Bed, LiOH: Lithium Hydroxide, MF: Multifiltration, PS: Phase Separator, VCD: Vapor Compression Distillation, VPCAR: Vapor Phase Catalytic Ammonia Removal Assembly, VRA: Volatile Removal Assembly

7.4.3 Food production system

Table 7.5 shows the ESM of the lunar farm food production system. This design value is based on LED lighting, hydroponics, and an inflatable structure. The initial mass of 6.51 kg/m^2 of the crop part in Table 7.5 is the total mass of N_2, CO_2, NH_3, and HNO_3 from Earth, and the mass of N_2 is calculated from the volume of the cultivation space and the mass of CO_2, NH_3, and HNO_3 was calculated based on the mass balance in Table 7.3.

The LED power required for crop cultivation shown in Table 7.1 was calculated assuming the biomass production per the number of photons (mol) by photosynthesis is 0.4 g/mol [8,23], and the photosynthetic amount per photon flux required for the production of 1,090 g (edible portion 562 g, non-edible portion 498 g) is 2,651 mol (1,090 g/0.4 g/mol). Assuming that the photosynthetic photons per joule of the LED are 1.66 μmol/J [15], the photosynthetic photon flux is 1,596,728 kJ (2,651 mol/0.00166 mol/kJ). If this energy is irradiated in 8 hours, the required power will be 44.4 kW/CM-d (1,596,728 kJ/36,000 s). Dividing this by the cultivation area of 80.2 m^2 gives 0.553 kW/m^2. The cooling (exhaust heat) was set to 20% of the LED lighting power based on the plant factory's data. Working hours 1.3 h/m^2-year is a figure assuming that most agricultural work is automated.

Table 7.5. Food production system for the lunar farm

Components	Initial mass	Volume	Electric power	Heat load	Logistics mass	Working Hours
	Kg/m^2	m^3/m^2	kW/m^2	kW/m^2	Kg/m^2-year	h/m^2-year
Crop portion	6.51	2.6	0.14	0.14	0	1.3
Lighting equipment	7.54	0.4	0.691	0.138	0.19	0.0027
Electric power system	2.77	0	0.02	0.02	1.07	0.0032
Mechanical system	4.1	0	0.1	0.1	0.5	0.1
Secondary structure systems (shelves)	5.7	0	0	0	0	0
Total	26.6	3.00	0.96	0.41	1.75	1.41
Primary structural system (inflatable)	9.16	0	0	0	0	0

7.4.4 Resource regeneration system

With the production of food, inedible parts corresponding to the amount of edible parts were generated. We calculate the ESM of the bioreactor based on the mass balance in Table 7.3. The dry mass of the inedible portion per person was 497.8 g/d. The wet mass before water addition was 736 g/d (inedible portion 497.8 g/d, water 238.2 g/d). If 2,175 g of water is added to bring the water ratio to 80% before treatment, the total amount will be 2,987 g (736 g/d, 2,251 g/d). Assuming that the density of the processed material was 1,000 g/L, the volume was 3.0 L/d (2,987 g/d/1,000 g/L). Assuming a reaction time of 20 day, the reaction vessel's size was 60 L/d (3.0 L/d × 20 d), that is, 0.06 m^3.

Next, based on the specifications of the methane fermentation facility (processing capacity 17,500 kg, device mass 865,000 kg, device volume 33,600 m^3, electric power 566 kW, cooling 361 kW) shown in the report [24] of the Low Carbon Social Strategy Center. Table 7.6 shows the specifications of a bioreactor that can process 497.8

g/person/d. The volume of 1.17 m^3 is large enough for 0.06 m^3. The volume is 1.17 m^3, including the reaction vessel and other equipment.

Table 7.6. Bioreactor on lunar farm

Mass	Volume	Electric power	Heat load	Logistics mass	Working Hours
Kg/CM	m^3/CM	kW/CM	kW/CM	Kg/CM-yr	h/CM-yr
30.0	1.17	0.02	0.01	TBD	TBD

7.5 Comparison of system design proposals

Fig. 7.2 shows the system configuration of the lunar farm. The system has eight subsystems of air revitalization (Air), biomass production (Biomass), food storage (Food), thermal control (Thermal), waste recycling (Waste), water process (Water), extravehicular activity (EVA) (not shown in Fig. 7.2), and human accommodations (Accommodations). Here, we compared five life support system design proposals: open system (OPEN), ISS system (regeneration of air and water) (ISS (A + W)), and three closed system (CLOSED 1, CLOSED 2, CLOSED 3). Of these, the closed system was composed of biomass production on the lunar farm. Compared with CLOSED 1, CLOSED 2 changed the number of rice and soybean cultivation shelves from one to two and CLOSED 3 changed it from one to three. The settings for the plant cultivation module (inflatable outer shell), excluding the food production system at this time, are as shown in Table 7.7. For example, CLOSED 1 has a floor area of 70.6 m^2, a cultivation space height of 3 m, and a volume of 267 m^3, including a 20% margin. If this is constructed with an inflatable structure without a shield, the outer shell mass will be 2,444 kg (267 m^3 × 9.16 kg/m^3). For the mass of 9.16 kg/m^3 per unit volume, the standard value [15] of NASA's advanced life support system was used.

For the food supply of six people, a plant cultivation space with a volume of 1,601 m^3 (267 m^3 × 6) and a mass of 14,661 kg (2,444 kg × 6) was required, which was equivalent to 11 modules of 150 m^3. If CLOSED 2 is used, there will be six modules, and if CLOSED 3 is used, there will be four modules. Additionally, there is one habitation module, one experimental module, and one utility module. These modules are covered and protected with regolith, as shown in Fig. 7.3.

Table 7.8 shows the ESM equivalency factor of the lunar base. The equivalency factor of electric power is a numerical value when nuclear power generation is used. The labor hours' equivalency factor varies depending on the available time, but the calculation method [21] was omitted.

Table 7.7. Settings for plant cultivation modules (inflatable outer shell)

	CLOSED 1	CLOSED 2	CLOSED 3
Cultivated area, m^2 per person	80.2	80.2	80.2
Floor area, m^2 per person	70.6	38.1	27.3
Floor area/cultivation area	0.88	0.48	0.34
Volume of plant cultivation space (including 20% margins), m^3 per person	267	144	103
Mass of Plant Cultivation Space, kg/person	2,444	1,319	944
Plant cultivation module volume (for six people), m^3	1,601	864	618
Plant cultivation module mass (for six people), kg	14,661	7,913	5,664
Number of plant cultivation modules (for six people)	11	6	4

Table 7.8 ESM- Equivalency Factor [21] for Lunar Base

Element	Equivalency factor
Mass kg/kg	1
Volume kg/m^3	9.16
Electricity (nuclear power use) kg/kW	76
Cooling kg/kW	102
Working hours kg/h	(variable)

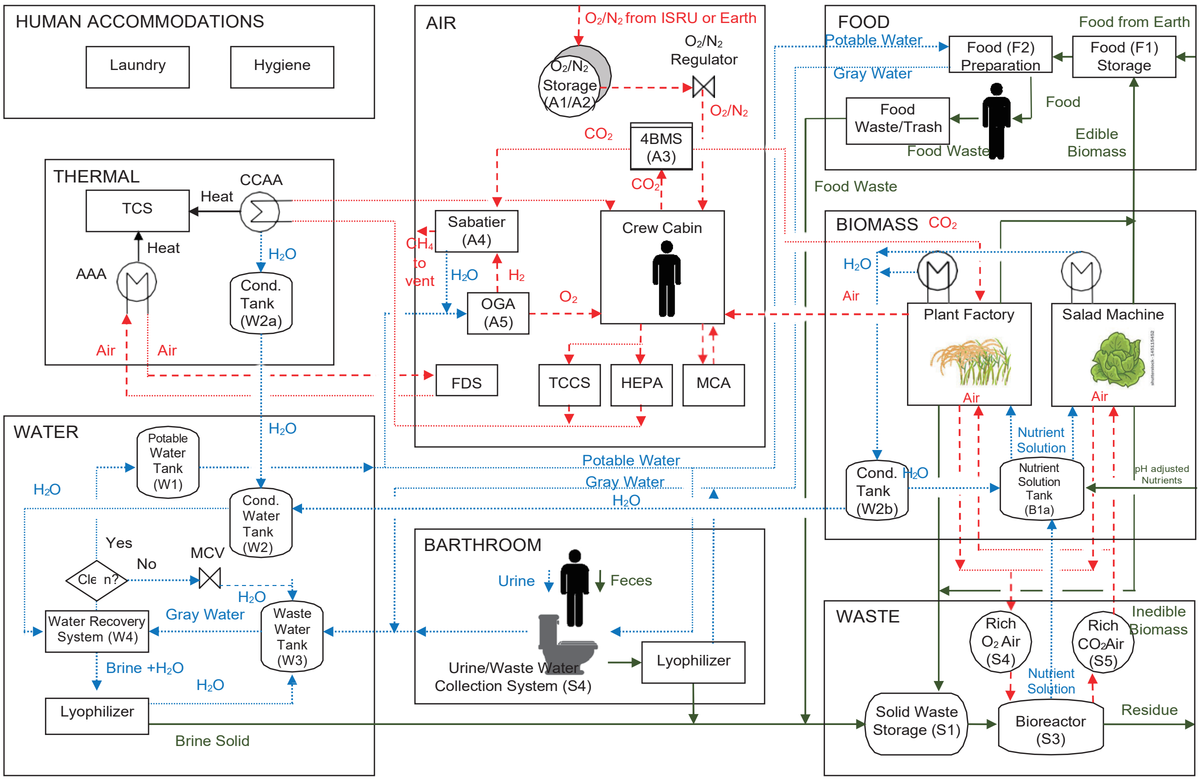

Fig. 7.2. Configuration of life support systems for lunar base including farm

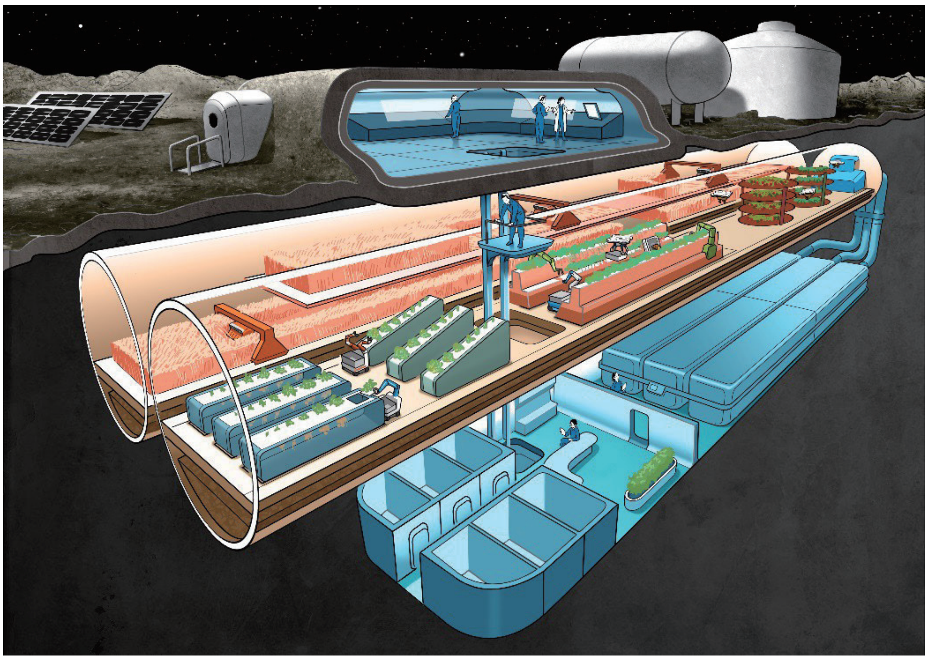

Fig. 7.3. Lunar base covered by regolith

Table 7.9 shows the calculation results of mass and ESM when six people live on the moon for 1 year. The graphs of OPEN, ISS (A + W), CLOSED 1, CLOSED 2, and CLOSED 3 are shown in Table 7.9 and Fig. 7.4 to 7.9. Fig. 7.4, 7.5, 7.7, and 7.8 show the initial mass, 1-year logistics mass, initial ESM, and 1-year ESM increment for each subsystem, Fig. 7.6 shows the time variation of the total mass of the five life support systems, and Fig. 7.9 shows the time variation of the ESM of the five life support systems. The number in parentheses is the regeneration rate in terms of mass. Finally, Fig. 7.10 shows the number of days in which the ESM of CLOSED 2 was less than that of ISS (A + W) and ESM of CLOSED3 was less than that of ISS (A + W) when the agricultural work automation rate was changed.

Comparison of initial and logistics mass (Table 7.9(a) (b), Fig. 7.4, Fig. 7.5)

Table 7.9 (a) and (b) show the initial mass of the five life support systems and the logistics mass for 1 year. The initial mass of CLOSED 1 was 19.3 times that of OPEN. In CLOSED 1, the air and water process subsystems' functions were replaced by biomass production, such that the initial mass of the two subsystems was less than the ISS (A + W), but the mass of the food production system was 26,534 kg. The initial mass of CLOSED 1 was much larger than that of OPEN.

Next, the initial masses when the number of rice and soybean cultivation shelves was set to two (CLOSED 2) to make the biomass production system less than in CLOSED 1 and when the cultivation shelves was set to three (CLOSED 3) that were 12.7 times and 10.4 times that of OPEN. CLOSED 2 and 3 had a less initial mass because of a less pressurized volume than CLOSED 1 but were still considerably larger than the initial mass of OPEN and ISS (A + W).

The logistics mass of CLOSED 1, 2, and 3 was 0.24, 0.22, and 0.21 times, respectively, that of OPEN. Biomass production could regenerate air (oxygen), food, and water and significantly reduce their logistics mass compared with OPEN and ISS (A + W).

Time-series comparison of initial mass and logistics mass (Fig. 7.6)

Fig. 7.6 shows the 1,800 days change of the total mass (initial mass and logistics mass) of the five life support systems. The mass of CLOSED 2 was less than OPEN after 550 days and less than ISS (A + W) after 900 days. The mass of CLOSED 3 was less than OPEN after 450 days and less than ISS (A + W) after 750 days.

Comparison of initial ESM and 1-year ESM increments (Table 7.9 (c) (d), Fig. 7.7, Fig. 7.8)

Table 7.9 (c) (d) shows the initial ESM of the five life support systems and the ESM increments when operated for 1 year. The initial ESM of CLOSED 1 was 44.4 times that of OPEN. CLOSED 2 was 33.1 times OPEN, and CLOSED 3 was 29.4 times OPEN. The 1-year ESM increments for CLOSED 1, 2, and 3 were 0.4, 0.3, and 0.3 times OPEN, respectively.

ESM time-series comparison (Fig. 7.9)

Fig. 7.9 shows the 4,000 days changes in ESM of the five life support systems. CLOSED 1 fell below the OPEN ESM after 3,600 days and never fell below the ISS (A + W) ESM within 4,000 days. CLOSED 2 fell below the OPEN ESM after 2,200 days and did not fall below the ISS (A + W) ESM within 4,000 days. CLOSED 3 was below the OPEN ESM after 1,850 days and below the ISS (A + W) ESM after 3,650 days. When rice and soybeans are cultivated in three stages, the system became more advantageous than the ISS (A + W) in approximately 10 years.

Rate of farming automation and the breakeven point (Fig. 7.10)

Fig. 7.10 shows the change in the mission period when the ESM of CLOSED 2 and 3 was less than the ESM of the ISS (A + W) when the agricultural work automation rate was changed. An automation rate of 0 indicated farm work at 13 $h/m^2/year$ [22], and 1 indicated full automation. The results shown in Fig. 7.1 to 7.9 are the values calculated at the automation rate of 0.9. As the automation rate drops to 0.8 and 0.7, the mission period in which the ESM of CLOSED 2 fell below the ESM of ISS (A + W) became remarkably longer. The breakeven point of CLOSED 3 was less sensitive to the automation rate decrease than in CLOSED 2. The automation of farm work on lunar farms was important for reducing operating costs.

Table 7.9 (a) Initial mass, (b) Logistics mass, (c) Initial ESM, and (d) ESM increments when operated for 1 year

Initial mass、 kg	OPEN (0%)	ISS(A+W) (37%)	CLOSED 1 (76%)	CLOSED 2 (78%)	CLOSED 3 (79%)
Air	585	846	653	653	653
Biomass	0	0	26,534	16,623	13,320
Food	0	0	321	321	321
Thermal	390	390	390	390	390
Waste	115	115	348	348	348
Water	164	1,062	141	141	141
EVA	196	196	196	196	196
Accommodations	35	35	115	115	115
Total	**1,485**	**2,644**	**28,698**	**18,787**	**15,484**
System/OPEN	**1.0**	**1.8**	**19.3**	**12.7**	**10.4**

Logistics mass, kg/year	OPEN (0%)	ISS(A+W) (37%)	CLOSED 1 (76%)	CLOSED 2 (78%)	CLOSED 3 (79%)
Air	1,705	28	28	28	28
Biomass	0	0	733	437	339
Food	4,073	4,073	149	149	149
Thermal	19	19	19	19	19
Waste	0	0	0	0	0
Water	6,462	2,206	3	3	3
EVA	757	757	757	757	757
Accommodations	3,024	3,024	2,131	2,131	2,131
Total	**16,041**	**10,108**	**3,819**	**3,524**	**3,425**
System/OPEN	**1.00**	**0.63**	**0.24**	**0.22**	**0.21**

Initial ESM, kg	OPEN (0%)	ISS(A+W) (37%)	CLOSED 1 (76%)	CLOSED 2 (78%)	CLOSED 3 (79%)
Air	730	1,110	900	900	900
Biomass	0	0	90,115	66,511	58,644
Food	0	0	339	339	339
Thermal	628	628	628	628	628
Waste	138	138	413	413	413
Water	179	1,338	145	145	145
EVA	382	382	204	204	204
Accommodations	35	35	231	231	231
Total	**2,093**	**3,631**	**92,974**	**69,371**	**61,503**
Total/OPEN	**1.0**	**1.7**	**44.4**	**33.1**	**29.4**

ESM increment, kg/year	OPEN (0%)	ISS(A+W) (37%)	CLOSED 1 (76%)	CLOSED 2 (78%)	CLOSED 3 (79%)
Air	1,705	39	104	85	78
Biomass	0	0	3,446	1,528	1,032
Food	4,073	4,073	149	149	149
Thermal	36	32	111	87	79
Waste	0	0	6	4	4
Water	6,462	2,206	3	3	3
EVA	984	929	757	757	757
Accommodations	3,024	3,024	2,462	2,377	2,349
Total	16,284	10,303	7,037	4,990	4,452
Total/OPEN	1.0	0.6	0.4	0.3	0.3

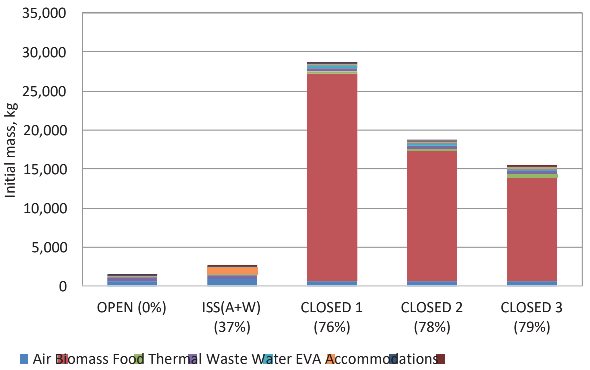

Fig. 7.4 Comparison of initial masses of the five system configurations

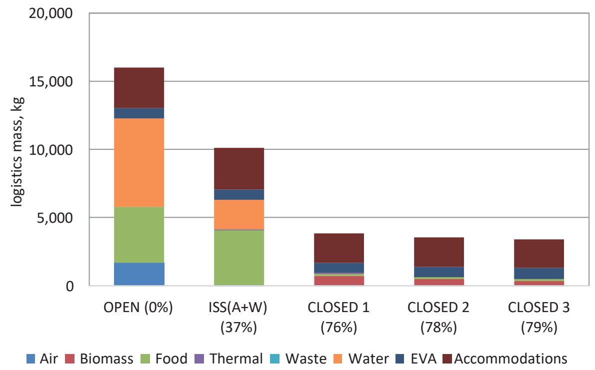

Fig. 7.5 Comparison of logistics mass of the five system compositions when operated for 1 year

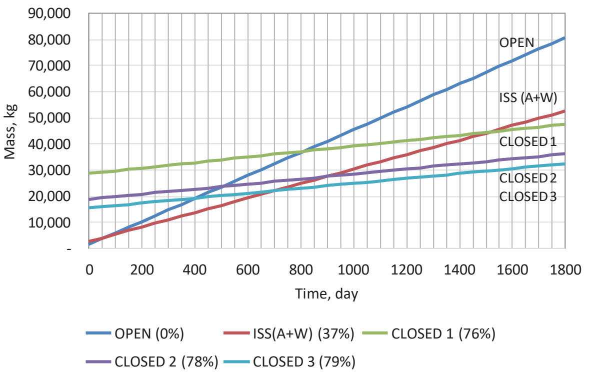

Fig. 7.6 Mass (initial + logistics) time change comparison of the five system configurations

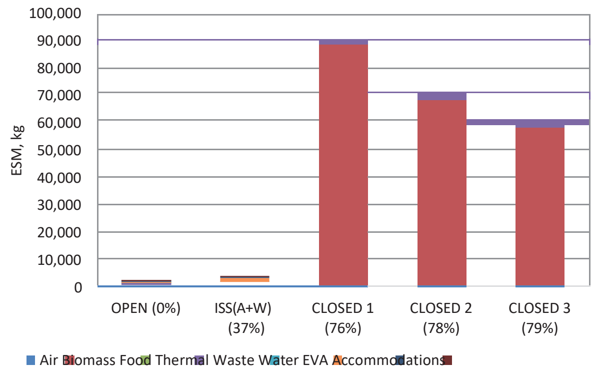

Fig. 7.7 ESM comparison of the five systems on day 0

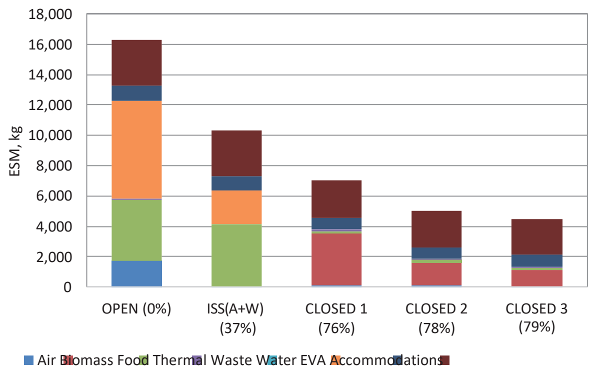

Fig. 7.8 One-year ESM incremental comparison of the five systems

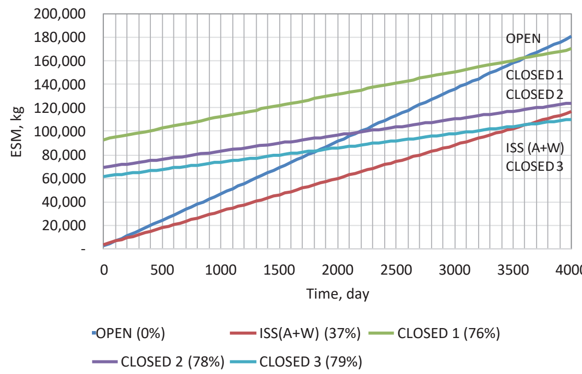

Fig. 7.9 Comparison of ESM time changes for the five system configurations

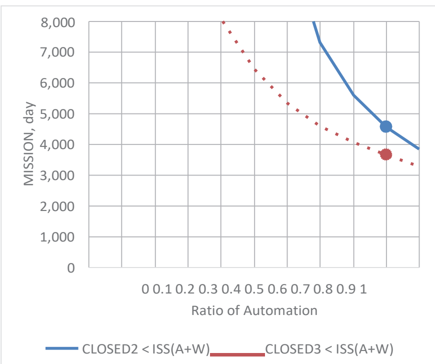

Fig. 7.10 Agricultural automation rate and breakeven point

7.6 Summary

We have developed a bioregenerative life support system analysis tool that allows us to consider introducing a lunar farm at a lunar base. We compared the mass and ESM of lunar-based life support systems, including biomass production systems, to introduce recent technologies, such as LEDs. When the number of cultivation shelves for crops with a large amount of cultivation increases and the space utilization efficiency is increased, the initial mass can be greatly suppressed. It was also confirmed that it is advantageous after 450 days from the total mass of the open system and after 750 days from the total mass of the ISS system. However, 1,850 and 3,650 days or more are required for the operation that is more advantageous than the open system and the ISS system, respectively, in the evaluation using ESM, including the labor hours, even if the number of cultivation shelves is increased and the space utilization efficiency is improved.

Here, it is shown that one of the lunar farms was more advantageous in terms of operating costs expressed in ESM than replenishing food from the earth in approximately 10 years when building materials and substances, such as water and oxygen, were procured on the moon and nuclear power was used. When using the eight types of crops envisioned at this time, multi-stage cultivation of rice and soybeans (approximately three stages) and automation technology, which have a large cultivation area, are particularly important for reducing operating costs.

Appendix 7A: Biochemical Stoichiometry

Biochemical stoichiometry [10)] was used in the mass balance analysis of life support systems. Biochemical stoichiometry was developed by Volk T. and Rummel J. D. to analyze the mass balance of closed ecosystems. Biochemical stoichiometry approximates the metabolites of living organisms with chemical formulas, creates a mass balance equation for the metabolism, and solves the mass balance equation based on mass conservation law to obtain an unknown metabolite [11)]. Four mass balance equations for plants, humans, waste process, and fertilizer production are shown.

<u>Plants</u>

The mass balance equation of plants consists of Equation (A1) and Equation (A2) in which "carbon dioxide, water, ammonia, and nitric acid" are changed to "proteins, fat, carbohydrate, fibers, oxygen" by photosynthesis.

Edible parts:

$$a_1 \cdot CO_2 + a_2 \cdot H_2O + a_3 \cdot NH_3 + a_4 \cdot HNO_3 \rightarrow$$

$$b_1 \cdot C_4H_5ON + b_2 \cdot C_{16}H_{32}O_2 + b_3 \cdot C_6H_{12}O_6 + b_4 \cdot C_6H_{10}O_5 + b_5 \cdot O_2 \quad \text{(A1)}$$

Inedible parts:

$$a_5 \cdot CO_2 + a_6 \cdot H_2O + a_7 \cdot NH_3 + a_8 \cdot HNO_3 \rightarrow$$

$$b_6 \cdot C_4H_5ON + b_7 \cdot C_{16}H_{32}O_2 + b_8 \cdot C_6H_{12}O_6 + b_9 \cdot C_6H_{10}O_5 + b_{10} \cdot O_2 \quad \text{(A2)}$$

<u>Human beings</u>

The human mass balance equation consists of the Equation (A3) in which "protein, fat, carbohydrate , fiber, and oxygen" changes to "urine, feces, other organic matter, carbon dioxide, and water."

$$e_1 \cdot C_4H_5ON + e_2 \cdot C_{16}H_{32}O_2 + e_3 \cdot C_6H_{12}O_6 + e_4 \cdot C_6H_{10}O_5 + e_5 \cdot O_2 \rightarrow$$

$$e_6 \cdot C_2H_6O_2N_2 + e_7 \cdot C_{42}H_{69}O_{13}N_5 + e_8 \cdot C_{13}H_{28}O_{13}N_2 + e_9 \cdot CO_2 + e_{10} \cdot H_2O \quad \text{(A3)}$$

<u>Waste process</u>

The mass balance equation for waste process consists of Equation A4 that changes "urine and oxygen" to "carbon dioxide, water, and nitrogen," Equation (A5) that changes "feces and oxygen" to "carbon dioxide, water, and nitrogen," Equation (A6), in which "other organic matter and oxygen" changes to "carbon dioxide, water, and nitrogen," and Equation (A7) in which "protein, fat, carbohydrate, fiber, and oxygen " changes to "carbon dioxide, water, and nitrogen."

Urine:

$$g_1 \cdot C_2H_6O_2N_2 + g_2 \cdot O_2 \rightarrow h_1 \cdot CO_2 + h_2 \cdot H_2O + h_3 \cdot N_2 \quad \text{(A4)}$$

Feces:

$$g_3 \cdot C_{42}H_{69}O_{13}N_5 + g_4 \cdot O_2 \rightarrow h_4 \cdot CO_2 + h_5 \cdot H_2O + h_6 \cdot N_2 \quad \text{(A5)}$$

Other organic matter:

$$g_5 \cdot C_{13}H_{28}O_{13}N_2 + g_6 \cdot O_2 \rightarrow h_7 \cdot CO_2 + h_8 \cdot H_2O + h_9 \cdot N_2 \quad (A6)$$

Inedible parts:

$$g_7 \cdot C_4H_5ON + g_8 \cdot C_{16}H_{32}O_2 + g_9 \cdot C_6H_{12}O_6 + g_{10} \cdot C_6H_{10}O_5 + g_{11} \cdot O_2$$
$$\rightarrow h_{10} \cdot CO_2 + h_{11} \cdot H_2O + h_{12} \cdot N_2 \quad (A7)$$

Fertilizer production

The mass balance equation for fertilizer production consists of the Equation (A8) in which "nitrogen and water" are changed to "ammonia and nitric acid."

$$h_{13} \cdot N_2 + h_{14} \cdot H_2O \rightarrow h_{15} \cdot NH_4 + h_{16} \cdot HNO_3 \quad (A8)$$

Appendix 7B Equivalent System Mass

Equivalent System Mass (ESM) [6] used by NASA was used to compare the entire system. ESM expresses the cost of a life support system by mass, volume, power, cooling, and working hours as shown in equation (B1), and calculates ESM by summing subsystems i = 1 to n.

$$ESM = \sum_{i=1}^{n} \left[\left(M_{I_i} \cdot SF_{I_i} \right) + \left(V_{I_i} \cdot V_{eq_i} \right) + \left(P_i \cdot P_{eq_i} \right) + \left(C_i \cdot C_{eq_i} \right) + \left(CT_i \cdot D \cdot CT_{eq_i} \right) + \left(M_{TD_i} \cdot D \cdot SF_{TD} \right) \right] \quad (B1)$$

M_{Ii}: Initial mass of subsystem i [kg]
SF_{Ii}: Initial mass storage factor of subsystem i [kg/kg]
V_{Ii}: Initial volume of subsystem i [m^3]
V_{eqi}: Pressurized volume-mass equivalent factor of subsystem i [kg/m^3]
P_i: Required power for subsystem i [kW_e]
P_{eqi}: Subsystem i's power-mass equivalent factor [kg/kW_e]
C_i: Cooling requirement of subsystem i [kW_{th}]
C_{eqi}: Cooling-mass equivalent factor for subsystem i [kg/kW_{th}]
CT_i: Crew time required for subsystem i [CM-h/yr]
D: Mission period [y]
CT_{eqi}: Crew time equivalent factor for subsystem i [kg/CM-h]
M_{TDi}: Time-dependent mass of subsystem i [kg/yr]
SF_{TDi}: Time-dependent mass storage factor of subsystem i [kg/kg]

The mass equivalency factors (V_{eq}, P_{eq}, C_{eq}, and CT_{eq}) convert non-mass parameters (V, P, C, and CT) to mass.

Appendix 7C Elemental technology candidate(s) for life support system

Table 7C1 shows the elemental technology candidates for the lunar-based life support system. Subsystem mass, volume, power, cooling, and labor hours are available in the references MSAD-04-0306 (Hanford, 2004) [21], NASA CR-2006-213694 (Hanford, 2006) [22], NASA JSC-47804 (Hanford, 2002) [25]. Table 7C2 shows the OPEN system, ISS (A + W) system, and CLOSED system.

Tabular 7C1 Six lunar base life support system element technology candidates

No.	Subsystem	Tech.	Mass Kg	Volume m^3	Power W_e	Cooling W_{th}	Resupply Mass Kg/d	Resupply Parts Mass Kg/yr	Resupply Volume m^3/yr	Crew time CM-h/yr	Ref. No
100	**Air Subsystem**										
110	**Atmospheric Control System**										
111	Atmospheric Pressure Control	ISS	119.4	0.26	70.5	70.5	0	0.00	0	0	20
120	**Atmosphere Revitalization System**										
121	Carbon Dioxide Removal	LiOH	0	0	0	0	0.00	365.00	1.095	0	
122	Carbon Dioxide Removal	4BMS/ISS	185.1	0.44	556.21	556.21	0.00	0.00	0	2.76	20
123	Carbon Dioxide Reduction	Sabatier	75.91	0.14	82.94	82.94	-3.59	0.00	0	0	20
125	Oxygen Generation	SPE/ISS	388.97	1.02	3421.67	1868.34	4.04	50.32	0	10.1	20
126	Gaseous Trace Contaminant Control	ISS	68.41	0.14	194.35	194.35	0.00	21.29	0.322	0	20
127	Atmosphere Composition Monitoring Assembly	ISS	54.3	0.09	103.5	103.5	0.00	0.00	0	0	20
128	Sample Delivery	ISS	35.11	0.04	0	0	0.00	0.00	0	0	20
129	System Airlock Carbon Dioxide Removal	ISS	181.3	0.23	397	397	0.00	0.00	0	0	20
180	**Gas Storage**										
181	Nitrogen Storage	High Pressure	1	0.00	0	0	0.02			0	22
182	Nitrogen Storage	Cryogenic	22	0.02	0	0	0.02			0	22
183	Oxygen Storage	High Pressure	118	0.09	0	0	3.59			0	22
184	Oxygen Storage	Cryogenic	139	0.11	0	0	3.59			0	22
190	**Fire Detection and Suppression**										
191	Fire Detection System	ISS	1.5	0	1.48	1.48	0	0.00	0	0.01	20
192	Fire Suppression System	ISS	6.8	0.04	0	0	0	0.00	0	0	20
200	**Biomass Subsystem**										
220	**Plant Growth Chamber / Salad Machine**										
221	Plant Growth Chamber	Drysdale	43004	436	1107923	1107923		1614.22		922	16
222	Salad Machine	Takashima	120	0.602	500	500		2.40		91.25	
223	Plant Growth Machine I	CLOSED 1	11873	1303	442610	176489		732.83		92	WG
224	Plant Growth Chamber unshielded I	CLOSED 1	14661								15
225	Plant Growth Chamber shielded		213038								15
226	Plant Growth Machine II	CLOSED 2	8710	792	392001	125880		437.10		50	WG
227	Plant Growth Chamber unshielded II	CLOSED 2	7913								15
228	Plant Growth Machine III	CLOSED 3	7656	622	375132	109011		338.52		36	WG
229	Plant Growth Chamber unshielded III	CLOSED 3	5664								15
260	**Food Subsystem**										
262	Food Storage without food	Shuttle	0	0	0	0	11.16	0.00	0	0	WG

	production										
263	Refrigerator/Freezer	ISS	321	2	0.204	0.228					22
264	Food Storage with biomass production	Lunar Farm	0	0	0	0	0.41	0.00	0	0	WG
300	**Thermal Subsystem**										
310	**Temperature and Humidity Control**										
311	Common Cabin Air Assembly	ISS	118.08	0.5	530.52	530.52	0		0	0	20
312	Avionics Air Assembly	ISS	12.4	0.03	175	175	0		0	0	20
313	Atmosphere Circulation	ISS	9.8	0.02	61	61	0		0	0	20
314	Atmosphere Microbial Control	ISS	100	0.27	0	0	0	19.06	0.13	3.33	20
320	**Internal Thermal Control System**										
321	Internal Thermal Control System	-	149.28	0.3	517.71	517.71	0		0	0	20
400	**Waste Subsystem**										
410	**Solid Waste Collection**										
411	Solid Waste Collection	ESDM	36.36	0.13	14	14	0	0.00	0	0	20
420	**Solid Waste Processing System**										
421	Solid Waste Treatment	Storage	78.33	2.18	0	0		0.00	0	0	20
422	Incinerator	ALS	200	1.4	0.3	1.3		10.00		0.2	22
423	Supercritical Water Oxidation	ALS	200	1.4	0.5	1.5				0.2	
424	Bioreactor	ALS	231	0.46	0	0.59		1.50		1059.00	22
425	Bioreactor	LCS	148	6	0.1	0.1					WG
500	**Water Subsystem**										
510	**Urine/ Waste Water Collection System**										
511	Urine/ Waste Water Collection System	ISS	4.55	0.02	4	4	0	1.62	0	0	20
512	Urine/ Waste Water Collection System	ALS	4.55	0.02	4	4	0	1.62	0	0	20
520	**Water Recovery System**										
521	Water Treatment Process	ISS WRS	541.63	1.93	788.76	788.76		1295.75	0	0	20
522	Water Treatment Process	VPCAR	557.56	1.69	4011.45	1808.87		100.96	0	0	20
523	Urine, Hygiene & Potable Water, and Brine Storage	ISS	133.34	0.35	13.68	13.68			0	0	20
524	Urine, Hygiene & Potable Water, and Brine Storage	ALS	205.12	0.53	19.81	19.81			0	0	20
525	Microbial Check Valve	ISS	3.56	0.01	0	0		1.41	0	0	20
526	Microbial Check Valve	ALS	6.67	0.02	0	0		2.65	0	0	20
527	Process Controller	ISS	36.11	0.08	156.18	156.18			0	0	20
528	Process Controller	ALS	63	0	180	180			0	0	20
529	Water Quality Monitoring	ISS	14.07	0.04	4.72	4.72			0	0	20
530	Water Quality Monitoring	ALS	14.07	0.04	4.72	4.72			0	0	20
531	Product Water Delivery System	ISS	37.99	0.09	2.65	2.65			0	0	20
532	Product Water Delivery System	ALS	58.37	0.14	3.83	3.83			0	0	20
540	**Water Storage**										
541	Hygiene Water Storage	-	132	1.32			14.70		0	0	
542	Potable Water Storage	-	27	0.27			3.00		0	0	
543	Urine Storage	-					9.02		0	0	
544	Waste Water Storage	-					4.80		0	0	
600	**Human Accommodations**										
610	**Clothing**										
611	Clothing	Supply					2.92		6.24	0	

612	Clothing	Laundry					0.12		0.26	0	
620	**Laundry Equipment**										
621	Water/Dryer	-	80	0.26	633.33	633.33	0.00		0	12.045	20
622	Detergent	-	0.01	0	0	0	0.35		0	0	20
630	**Whips**										
631	Hand/Face/Shower Wet Whips	-					0.31				
640	**Miscellaneous Items**										
641	Miscellaneous Items	-					5.06				
642	N_2		35.42								
700	**Extravehicular Activity**										
711	Maximum Absorbency Garments	-	196	0.82			0.05		0.0001	44.8	20
712	Carbon Dioxide Removal (LiOH)	-					0.50		0.0015		
713	Airlock Recycle Pump for EVA	-			1000	1000	0.48		0.0014		
714	Oxygen Recharge Compressor Assembly for EVA	-					0.27		0.0008		
715	Food, O_2, and Water Add	-					0.77		0.0023		

Table 7 C2 OPEN, ISS (A + W), CLOSED system configuration

	Subsystem	OPEN system	ISS (A+W) system	CLOSED system
1	Air	111, 121, 126, 127, 128, 129, 181, 183, 191, 192	111, 122, 123, 124, 126, 127, 128, 129, 181, 183, 191, 192	111, 122, 126, 127, 128, 129, 181, 191, 192
2	Biomass			223, 224(CLOSED 1) 226, 227(CLOSED 2) 228, 229(CLOSED 3)
2	Food	262	262	263, 264
3	Thermal	311, 312, 313, 314, 321	311, 312, 313, 314, 321	311, 312, 313, 314, 321
4	Waste	411, 421	411, 421	423, 425
5	Water	511, 541, 542	511, 521, 523, 525	511, 523, 525
6	Accommodations	611, 631, 641	611, 631, 641	612, 621, 622, 631, 641
7	EVA	711, 712, 713, 714, 715	711, 712, 713, 714, 715	711, 712, 713, 714, 715

The subsystem numbers correspond to the numbers in Table 7C1.

Citations

1) Cabinet Office, Government of Japan, Comprehensive Strategy on Science, Technology and Innovation 2014 -Bridge of Innovation toward Creating the Future -, Cabinet Decision, 2014.

2) JAXA, Space Exploration Innovation Hub, http://www.ihub-tansa.jaxa.jp/english/index.html [cited 20 February 2018].

3) Wheeler, R. M., Agriculture for Space: People and Places Paving the Way, Open Agriculture 2017 2, 14-32, 2017.

4) Gitelson, J. I., Terskov, I. A., Kovrov, B. G., Lisovskii, G. M., Okladnikov, Yu. N., Sid'ko, F. Ya., Trubachev, I. N., Shilenko, M. P., Alekseev, S. S., Pan'kova, I. M., and Tirranen, L. S., Long-term experiments on man's stay in biological life-support system, Advances in Space Research, 1989;9(8):65-71.

5) Packham, N. J., The Lunar-Mars Life Support Test Project: the Crew Perspective, https://lsda.jsc.nasa.gov/books/ground/1.3Crewmembers.pdf [cited 20 February 2018].

6) Tako, Y., Komatsubara, O., Tsuga, S., Arai, R. et al., Circulation of Water in Addition to CO_2, O_2 and Plant Biomass in an Artificial Ecosystem Comprised of Humans, Goats and Crops During Three 2-Weeks Closed Habitation Experiments Using CEEF, SAE 2007-01-3091, 2007.

7) Dong C., Fu Y., Xie B., Wang M., and Liu H., Element Cycling and Energy Flux Responses in Ecosystem Simulations Conducted at the Chinese Lunar Palace-1, Astrobiology. January 2017, 17(1), 78-86.

8) Goto, E., Plant Cultivation and Light Environment Control under Artificial Light, http://www.academy.nougaku.jp/sympo/pdf/20131109sympo/20131109goto.pdf [cited 20 February 2018].

9) Goto, E., Matsumoto, H., Ishigami, Y., Hikosaka, S., Fujiwara, K. and Yano, A. 2014. Measurements of the photosynthetic rates in vegetables under various qualities of light from light-emitting diodes. Acta Horticulturae, 1037: 261-268.

10) Ono, E., Usami, H., Fuse, M., and Watanabe, H., Operation of a Semi-Commercial Scale Plant Factory, American Society of Agricultural and Biological Engineers, 2011.

11) Miyajima, H., Ishikawa, Y., Arai, R., Tako, Y., and Nitta, K., Considerations of Material Circulation in CEEF Based on the Recent Operation Strategy, SAE Technical Paper 2003-01-2453, 2003.

12) Miyajima, H., Logistics and Life Support Systems Analysis for High-Mobility Exploration on a Lunar Surface, 43rd International Conference on Environmental Systems, AIAA-2013-3377, 2013.

13) Discussions in JAXA Innovation Hub Lunar Farm Working Group, 2017.

14) Ministry of Health, Labor and Welfare (MHLW), Dietary Reference Intakes for Japanese (2015), http://www.mhlw.go.jp/file/06-Seisakujouhou-10900000-Kenkoukyoku/Overview.pdf [cited 20 February 2018].

15) Anderson, M. S., Ewert, M. K., Keener, J. F., and Wagner, S. A., Advanced Life Support Baseline Values and Assumptions Document, NASA, TP-2015-218570, 2015.

16) Hanford, A. J., Advanced Life Support Baseline Values and Assumptions Document, NASA, CR-2004-208941, 2004.

17) Tobias, B., Garr, J. and Erne, M., 2011: International Space Station water balance operations, Proceeding of 41st International Conference on Environmental Systems, AIAA 2011-5150.

18) Rummel, J. D., and Volk, T., 1987: A modular BLSS simulation model, Advances in Space Research, 7(4), 59-67.

19) Volk, T., and Rummel, J. D., 1987: Mass balances for a biological life support system simulation model, Advances in Space Research, 7(4), 141-148.

20) Hanford, A. J., Subsystem Details for the Fiscal Year 2004 Advanced Life Support Research and Technology Development Metric, MSAD-04-0306, 2004.

21) Hanford, A. J., Advanced Life Support Research and Technology Development Metric - Fiscal Year 2005, NASA/CR-2006-213694, 2006.

22) Drysdale, A. E. et al., Advanced Life Support Systems Modeling and Analysis Project Baseline Values and Assumptions Document, JSC 39317, 1999.

23) Patterson, R. L., Giacomelli, G. A., Hernandez, E., Yanes, M., and Jensen, T., Poly-Culture Food Production and Air Revitalization Mass and Energy Balances Measured in a Semi-Closed Lunar Greenhouse Prototype (LGH), ICES-2014-167, 2014.

24) The Center for Low Carbon Society Strategy (LCS), Methane Production from Biomass Wastes by Anaerobic Fermentation (First step), LCS-FY2013-PP-05, 2014.

8. FUTURE CHALLENGES

8.1 Plant cultivation in low-gravity environments

Low gravity can affect cultivation equipment and the cultivation environment. It was suggested from the results of a short-term microgravity experiment utilizing aircraft flight that convection disappears because of the absence of gravity, and heat exchange between the plant and the surrounding environment is suppressed, causing a rise in temperature of the plant that reduces fruit set. Additionally, it was suggested that low gravity might have a considerable effect on the water distribution in the rhizosphere (in the medium) and the environmental control by the cultivation system according to a recent short-term gravity fluctuation experiment using the parabolic flight of an aircraft that the gravity condition was partially changed by gravity of 1 G or less. Therefore, it is preferable to verify the effect of low gravity on the cultivation system. If verified by microgravity, there are a few problems even with partial gravity.

The necessity of experiments with partial gravity has been discussed. However, because of the Centrifuge Accommodation Module (CAM) discontinuation, which was planned to be installed on the ISS, experiments are being conducted using individual devices developed by each space agency. JAXA has developed an experimental device with a centrifuge called a Cell Biology Experiment Facility, CBEF, and uses it for scientific research set in “Kibo” , which is the Japanese experimental module. Because the diameter of the centrifuge of the CBEF is approximately 25 cm, if a plant cultivation unit is installed in the centrifuge, the plant growth space inside the unit will be approximately 5 cm in height. In the future, it is expected that the centrifuge of the CBEF will be enlarged, and a large crop cultivation device will be installed to improve the experimental environment for conducting low-gravity experiments. Because the operation of the ISS is effective until 2024 (at the time of writing), it is desirable to proceed with the adjustment as soon as possible. In particular, to verify the elemental technologies for the plant cultivation system's environmental control because of the difference in the gravity environment, assuming the moon gravity condition of 0.17 G and the Mars gravity condition of 0.38 G. Until now, the setting was for microgravity/1 G in-orbit control experiments. However, it is expected that the equipment environment will be improved in consideration of low gravity/1 G control experiments, low gravity/microgravity, and experimental patterns that make the gravity conditions variable.

The cultivation equipment mounted on the centrifuge in the current CBEF has restrictions related to power and communication and the dimensions. Moreover, it is expected that it will be very difficult in terms of cost and schedule to manufacture a cultivation unit to be mounted on the turntable of the centrifuge. Therefore, to verify the phenomena that occurs because of low gravity, such as that on the lunar surface and the surface of the planet in the future, it is necessary to set up a plant cultivation area equipped with at least lighting, a fan, an observation system, and a control communication system in the ISS.

8.2 Instrument configuration, devices

Regarding the system examined by the working group, it is necessary to examine the equipment configuration and equipment design to realize it concretely. However, because some technologies can be realized immediately but some of those that require research and development, it is necessary to identify key elemental technologies and demonstrate the technologies on the ground before conduct system design concretely. The identified elemental technologies will be required for participants at the Request for Proposal (RFP) of the JAXA Space Exploration Innovation Hub Center, and hopefully Japan's cutting-edge research and development will be conducted under the scheme.

8.3 Facilities such as lighting and air conditioning

One of the reasons why plant factories have become popular is the introduction of LEDs. Because the lunar farm is supposed to be an artificial light type plant factory, improving cultivation efficiency and reducing costs using LEDs are important factors. LEDs used in plant factories on the ground should be usable for space, but it is necessary to study the optimum LED by reviewing the temperature conditions because of the influence of low gravity and potential low pressure. Similarly, it is necessary to consider air conditioning equipment for controlling the temperature and air environment that meets the lunar farm conditions.

At the ISS, the concentration of CO_2 is higher than that in the atmosphere on Earth because of the constraints of life support systems. There is usually a high concentration environment of approximately 3,000 to 5,000 ppm. Therefore, when a cultivation test was conducted on potatoes at 5,000 ppm at the Tsukuba Space Center's ground laboratory, tuberous root growth was observed even in the high CO_2 group. However, a dedifferentiated callus-like mass appeared on the above-ground stem, which seemed to be a physiological disorder.

Fig. 8.1 CO_2 condition 5,000 ppm (Display is reduced because the door was opened)
Above-ground potatoes grown with LEDs
(Cultivated at Tsukuba Space Center Space Experiment Building in August 2018) Photo courtesy of JAXA
Red (peak wavelength 655 nm)/blue (peak wavelength 447.5 nm), Red-blue ratio 3:1, 400 μmol m^{-2} s^{-1} (irradiation distance 200 mm), Humidity 70–80%

To date, it has been reported that physiological disorders occur in tomato seedlings when grown under conditions involving high CO_2 (2000 ppm) and monochromatic (red or blue) LEDs in cultivation examples of artificial light type plant factories [1) 2)]. It has been suggested that the phenomenon of leaf swelling and deformation during LED cultivation may be related to ultraviolet rays and other unexplained light stimuli [3)]. Generally, an increase in yield can be expected in a high CO_2 environment. However, it has been reported that the effect on yield is low under the strong light when the light period is 24 hours in a high CO_2 environment. Some potato varieties have been reported that the effect on yield is low under the strong light condition when the light period is 24 hours in a high CO_2 environment[4)]. It has been reported that potato yield under 800 ppm CO_2 condition was the same as the yield of that in 400 ppm CO_2 concentration under light condition such as 1,000 μm^{-2} s^{-1}. [4)]

Thus, in a closed ecosystem where CO_2 concentration tends to be high because of the limits of physicochemical treatment, it is expected that the effect of yield will change depending on the intensity of the light environment. Additionally, because the element of low gravity is added, it is necessary to set the optimum conditions according to the growing conditions for efficient cultivation. Furthermore, air conditioning, control of atmospheric components in a closed environment, or at least environmental monitoring, is essential.

To prevent physiological disorders and obtain high-quality crops, it may be practical to add ultraviolet and infrared regions to red-blue LEDs. Healthy growth of crops contributes greatly to the increase in yield, and it is important to study lighting specifications for that purpose. It is also known that there are differences in wavelength sensitivities depending on the plant species and varieties. The selection policy, such as LED wavelength, changes depending on whether the growth rate, power consumption, or crop morphology is emphasized to set an appropriate amount of light and light quality.

Regarding plant cultivation using LEDs in the plant factory, research and practical application are progressing for leafy vegetables, such as lettuce, but for fruiting crops, such as tomatoes premised on reproductive growth, the solar-type is the mainstream in the greenhouse for facility horticulture. For tomatoes, an artificial light type plant factory is used to supply high quality and well-grown seedlings in a short period, and the fruiting stage is conducted at a solar-type plant factory using sunlight. If the cost reduction progresses in the future, it is conceivable that the entire growth process will be shifted to cultivation in an artificial light type plant factory. Additionally, the data are scarce because there are few reports of cultivation of potatoes under LEDs, experimental results regarding space will be valuable data for the cultivation of potato in plant factory.

Additionally, the light environment is important, such as irradiating with ultraviolet light to blue light, to promote the synthesis of plant functional components. It has been reported that the anthocyanin and ascorbic acid contents increase when strawberry fruits are irradiated with ultraviolet rays by LEDs [5)]. Because antioxidants are important for the health care of astronauts, there is a great advantage in enhancing the functionality of plants by lighting.

The growth of plants requires reddish light at approximately 660 nm, which is related to photosynthesis, and the formation of plant morphology requires blue light at approximately 460 nm. The space plant experiment unit developed by JAXA had adopted red and blue LEDs because of power constraints. Recent studies have suggested that green light (approximately 550 nm) also has physiological significance. It has also been noted that ultraviolet rays and far-red light are necessary for healthy growth and increased functional components. Therefore, when selecting LEDs for the cultivation module on the lunar farm or designing experimental equipment to demonstrate growth at the ISS before lunar activity, it is necessary to make the lighting device consider these results.

8.4 Seedlings

Plant seeds can be preserved, but complete sterilization of mold on the seed epidermis is difficult, depending on the seed shape. Additionally, some crops need to be transported by seedlings. It is necessary to study the storage form and storage conditions for transportation. Even within the cultivation module, consideration must be given to providing edible groups and culture areas for seeds and maintenance.

8.5 Food and resource expansion

In this report, eight cultivated crops have been set and examined. Naturally, this needs further expansion in the future to improve the eating habits of astronauts. Increasing the number of cultivated crops will increase the equipment required, leading to increased costs, and efficient expansion of crop species with a development for reducing operational load is required. When mushrooms and fruit trees can be cultivated, the variety of menus will expand dramatically.

Citations

1) H. Misu, M. Mori, S. Okumura, S. Kanazawa, N. Ikeguchi, R. Nakai, High-Quality Tomato Seedling Production System Using Artificial Light, SEI Technical Review No. 192, 132-137, 2018.
2) Y. Watanabe, T. Yasuda, T. Yoneda, A. Nakano, Examination of Irradiation Conditions Using LED Light for the Growth of Tomato Seedlings, Bulletin of the National Institute of Vegetable and Tea Science 15, 57-66, 2016.
3) G. Massa, H.-H. Kim, R. Wheeler, C. Mitchell, Plant Productivity in Response to LED lighting, HortScience 43(7), 1951-1956, 2008.
4) R. Wheeler, T. Tibbitts, A. Fitzpatrick, Carbon Dioxide Effects on Potato Growth under Different Photoperiods and Irradiance, Crop Science 31, 1209-1213, 1991.
5) H. Fukuda, T. Wada, Kokura, T. Ogura, Taste and safety of vegetables grown in plant factory and technical issues, Productivity improvement of plant factory, cost reduction technology and business construction -The whole picture of the plant factory that is attracting attention now. 40-45, 2015.

9. SUMMARY

9.1 Summary of activities of the Lunar Farming Concept Study Working Group

The activities of the Lunar Farm Concept Study Working Group, which has been implemented since 2017, were deepened by active discussions about the lunar farm realized thanks to the participation of many of the most knowledgeable experts in Japan. At first, we had an image like the one shown below, and these activities started with discussing about what kinds of experts we should gather opinions from. In this section, we will summarize the overview provided by the Lunar Farm WG Report.

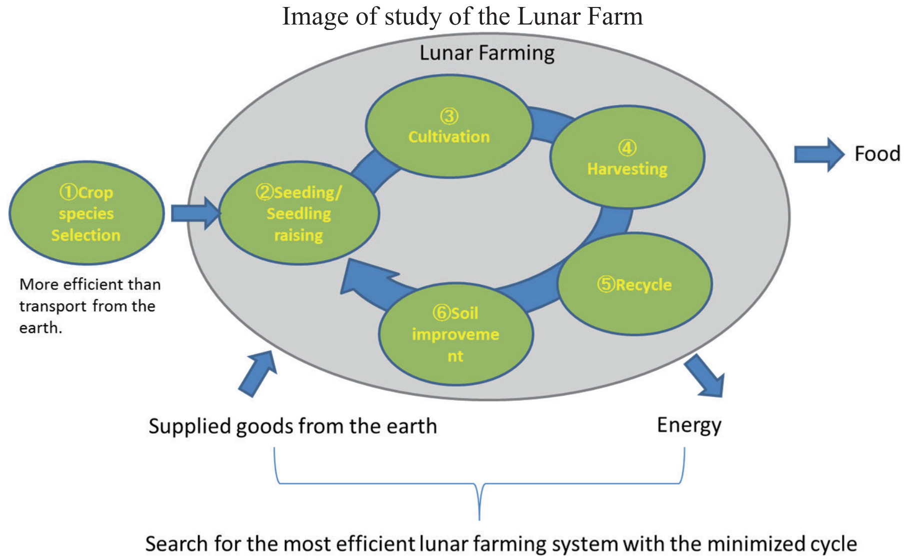

Fig. 9.1 Image of study of the Lunar Farm (created by the Secretariat)

9.1.1. Background of the study

At the start of the study, we proceeded with the conditions of the moon and the assumptions, as well as the hypotheses underlying the discussion. Although many of the physical conditions on the lunar surface are fixed, we advanced our discussions by assuming two situations, namely a 6-person scale at the beginning of settlement and a 100-person scale looking into a certain future, to discuss the efficiency of the scale and to unify the sense of scale of the system. Although there were also discussions about the use of sunlight, taking into consideration the need to protect a lunar farm from radiation and meteorites, many experts suggested that the merits from using LEDs after converting the sunlight into electricity on a solar cell panel exceed the merits from proactive use of sunlight.

By advancing discussions in each system, we were able to extract common goals such as resource-saving, space-saving, and workload-saving, to summarize the concept of lunar farming.

9.1.2. Overall picture of the lunar farm

Fig. 9.2 shows the overall picture, the 6-person scale and 100-person scale of the lunar farm. In the 6-person scale farm, the living area is covered with an embankment, the cultivation area is reclaimed in the basement, and underneath this, the safest area, is the residence area. In the cultivation area, a cultivation system for 8 selected crop species was designed by calculating the area for cultivation for each crop species according to the crop quantity allowing the consumption of the amount of energy and nutrients required for life at a 6-person scale.

In the 100-person scale farm, we provided a long-distance cylindrical cultivation area allowing efficient gantry-style cultivation of rice, which requires the largest area for cultivation. By developing 6 areas like this, we provided a route to gather the harvest in the middle, and a structure that enables the transport of waste residues to be carried into recycling facilities on the outer periphery. The living area in the middle and the residence area underground are the same as in the 6-person scale farm. In each cultivation area, we can see the structure of the high-efficiency cultivation system introduced in Chapter 5.

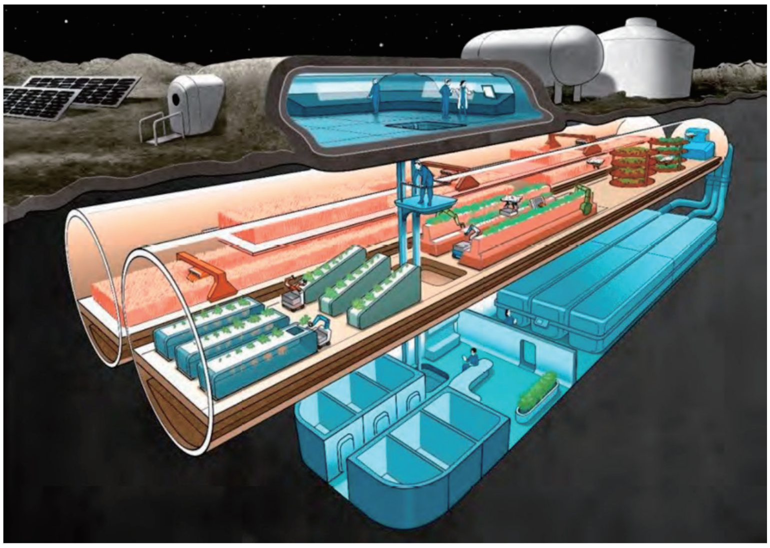

Fig. 9.2 Overall image of Lunar Farm (6-person scale) Fig. 7.3 re-posted

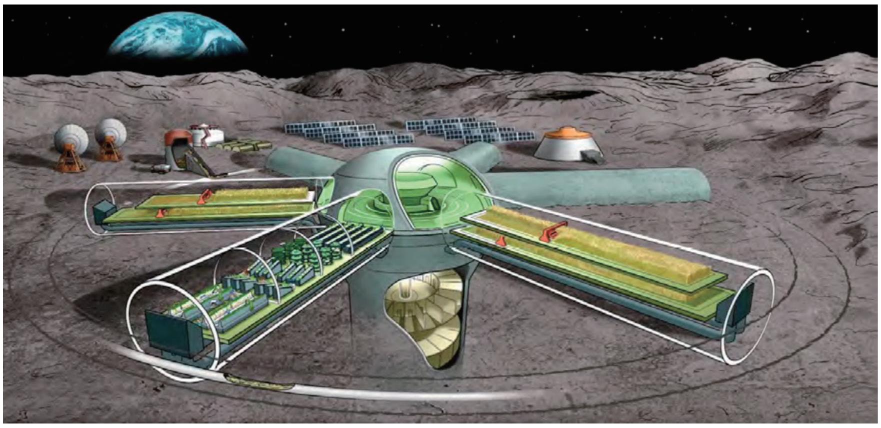

Fig. 9.3 Overall image of Lunar Farm (100-person scale)

9.1.3. Cultivation system

In Group 1, in order to study the cultivation system, we organized the basic points to remember about controlling the crop cultivation environment in the lunar farm. Items that needed to be examined included light, temperature, humidity, CO2, airflow, and rhizosphere environment, and we summarized the points to remember about each. We also introduced the challenges for cultivating crops in microgravity.

Taking the above into consideration, we comprehensively organized the system function, structure, cultivation method/conditions and management that made use of knowledge from plant factories on Earth. In the appendices, we summarized the management of each of the 8 crop species at each cultivation stage, in the form of a cultivation calendar.

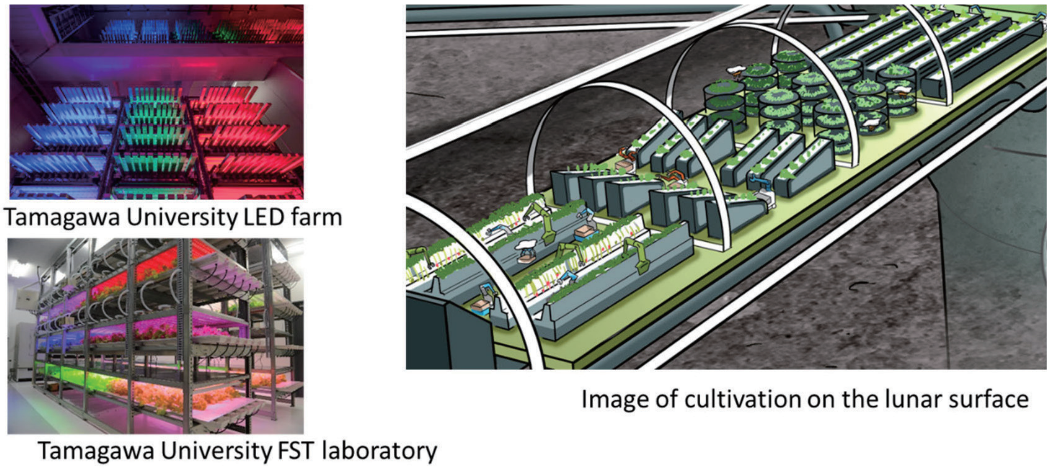

Fig. 9.4 Cultivation area image

9.1.4. High-efficiency food production

Group 2 considered the construction of a highly area-efficient cultivation system which allows highly efficient plant production. We also studied a cultivation system that uses dry fog (hydroponic mist) as a way to minimize the use of resources, particularly water and light, as well as an automated harvesting system which minimizes the labor required of astronauts. Furthermore, a monitoring system to understand the cultivation environment and growth status of crops is an important element for automation as well.

In Fig. 9.5, the top left figure shows a rice harvesting operation by gantry systems with cutting and threshing devices like combine harvesters, while the top right figure shows a potato cultivation system equipped with a selective harvesting robot, where irrigated by a dry fog system. On the bottom right, we see stackable round board growing systems for tomato plants where drone-UAVs can harvest and measure photosynthesis activities of plants using blue light excitation-fluorescence reaction. Finally, the bottom left picture shows a cooperative multirobot system for strawberry harvesting and managing.

In addition to these robots, another automation system for strawberry pollination operation is described in Chapter 5.

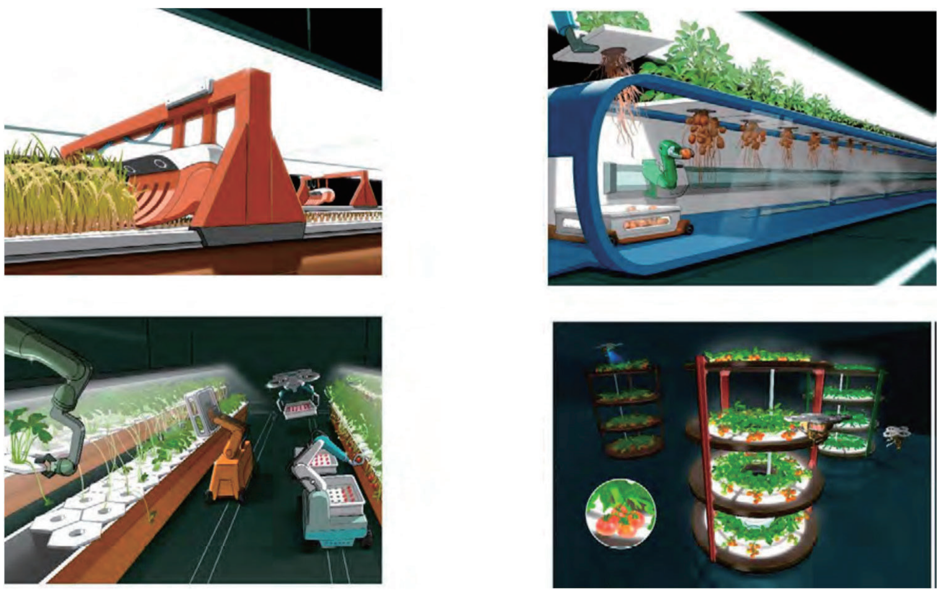

Fig. 9.5 Images of high efficiency plant training systems adaptable for robotic harvesting and managing operations.

9.1.5. Substance circulation system

Group 3 studied the resource circulation system to process waste materials produced on the moon and re-use elemental resources for plant production. As topics of discussion, the group examined the supply of elements during first settlement on the moon, the circulated use of microorganisms and culture solutions, microorganism treatment by methane fermentation, and use of residues, urine waste, and stool for composting. In addition, although the moon surface is covered with sand called regolith, which is similar to volcanic ash and has poor drainage that is not suitable for plant cultivation, we also conducted cultivation experiments using regolith mimics, as an example of using lunar surface minerals as resources. Fig. 9.6 shows an image of a container that gathers plant residues to advance methane fermentation, and a resource circulation system for forming nutrient solutions.

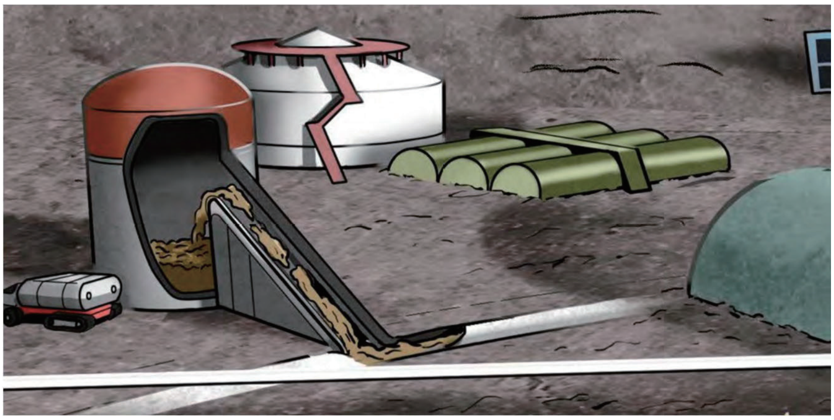

Fig. 9.6 Image of a substance circulation system

9.1.6. Other matters to consider

Group 4 considered the past and present studies and history related to space farming around the world, including Japan, in addition to leading the study of the overall system. In particular, in Japan, we referred to the experiments performed by the Aomori Institute of Environmental Sciences in Rokkasho Town, as they were responsible for many pioneering efforts.

We also selected 8 crop species, calculated the cultivation area needed to meet the energy and nutrient requirements that can be extracted from them, and proposed examples of recipes for meals that can be created using these 8 crop species.

To examine and assess the overall system, we studied the structure and scale of the lunar farm from the viewpoint of the design of a life maintenance system, derived the relationship between initial weight and supply mass, then examined the breakeven point where local production is more efficient than supplying food from earth.

9.2. Achievements of the Space Exploration Innovation Hub Center

Based on the discussions of the Lunar Farm Concept Study Working Group, in 2017 and 2018 the Space Exploration Innovation Hub Center made two calls for research proposals, established four research topics, and started eight joint research projects (Table 9.1). They will continue to perform research and development that satisfy both the need for new technology on Earth, as well as essential technology to realize lunar farming in the future. Since we presume that the technology obtained from these projects will see various uses, such as technology validation at the ISS and Showa Station in the South Pole, as well as deployment by businesses on Earth, we will examine and promote the places where the results of joint research can be applied to, so that we may apply these new technologies in lunar farms in the future.

Table 9.1 Achievements of the Space Exploration Innovation Hub

Research topic	Theme	Research site
Demonstration of cultivation of new crops assuming a lunar farm	Research on farm systems that are free from diseases and insects and can be backed up in an emergency using bag culture technology	Takenaka Corporation, Kirin Company, Limited, Chiba University, Tokyo University of Science
	Development of mass plasma processing technology for seeds to realize grain production	Kyushu University, Kenix Co. Ltd.
	Development of elemental technology for high-calorie crop cultivation system on a lunar farm	Chiyoda Corporation, Mebiol Inc.
	Fundamental study on a fully-closed and completely hydroponic artificial cultivation system for edible potato	Tamagawa University, Panasonic Corporation
Development of protein material applicable to plant production	Development of high-performance artificial structural protein material applicable to plant production	Spiber Inc.
Water-saving plant cultivation system using dry fog assuming a lunar farm	Development of indoor dry fog cultivation system with improved water-use efficiency	IKEUCHI & CO., Ltd., Osaka Prefectural University
A compact protein production system that does not rely on grains	Development of resource-saving and compact protein production system using the edible algae spirulina	Chitose Laboratory Corp., Tavelmout Corp., IHI Aerospace Co., Ltd. Fujimori Kogyo Co.,LTD.

9.3. Final remarks

This report is a valuable result of the first full-scale efforts in Japan towards space farming. Thus far, Japan has produced important results in plant research under a microgravity environment through space experiments. On this occasion, using this knowledge and experience, we examined a food production base on the lunar surface with gravity present. Knowledgeable persons and experts from a wide range of fields were able to gather together to discuss and build up a well-rounded report that exceeded the original goal. We hope that this report will inspire increased interest towards lunar farming, and lead to the acceleration and development in various efforts, including in that of relevant fields.

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