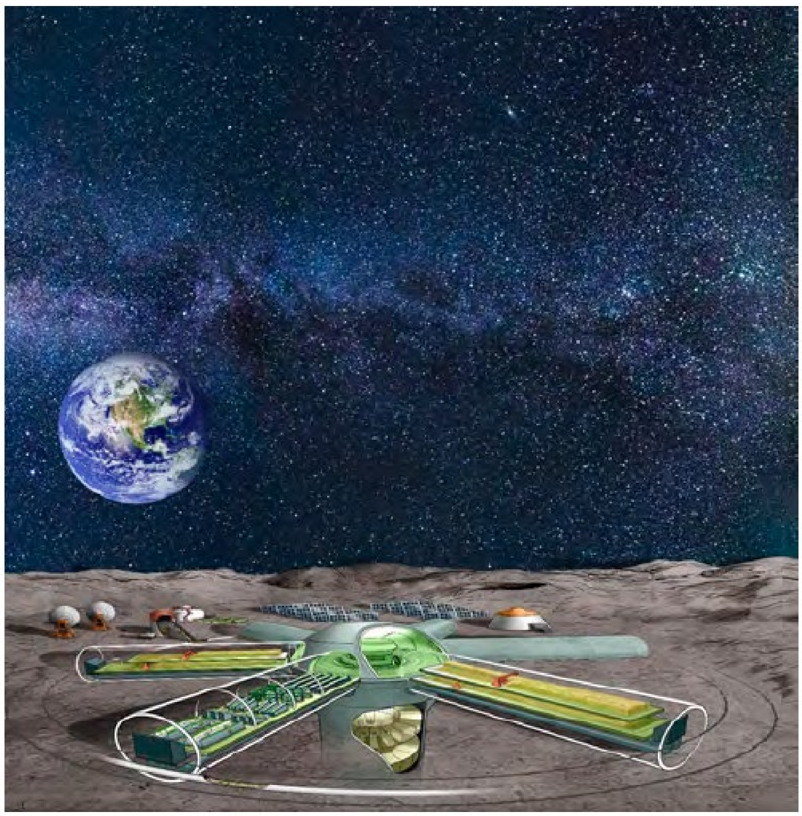
ISSN 2433-2232(Online)
JAXA-SP-19-001

Report of Lunar Farming Concept Study Working Group 1st

(summary version)

Lunar Farming Concept Study Working Group



June 2019

Japan Aerospace Exploration Agency (JAXA)

Report of Lunar Farming Concept Study Working Group 1st

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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	Instructor 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 of Environmental Sciences and Technology, Graduate School of Life and Environmental Sciences, Osaka Prefecture University	Controlled ecological life support systems focusing on plant cultivation and environmental monitoring and control
Masaharu Kojima	Shoei Co., Ltd.	Farming consultant
Naoshi Kondo	Professor, 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	Associate 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	Researcher, Kyushu Okinawa Agricultural Research Center, National Agriculture and Food Research Organization	Artificial light 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, International University of Health and Welfare	Closed environment ecosystem engineering
Sachiko Yano	Associate Senior Engineer, Kibo Utilization Center, Department of Manned Space Flight Directorate, JAXA Special Researcher, Science and Technology Prediction Center, National Institute of Science and Technology Policy (NISTEP)	Space experiments, plant cultivation experiments
Hiroyuki Watanabe	Professor, Department of Life Science, 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 harvesting, unmanned/robot-controlled technology, etc.	Sowing/growth Cultivation/harvest	Kondo (Lead) Ohba Ito
(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.

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.

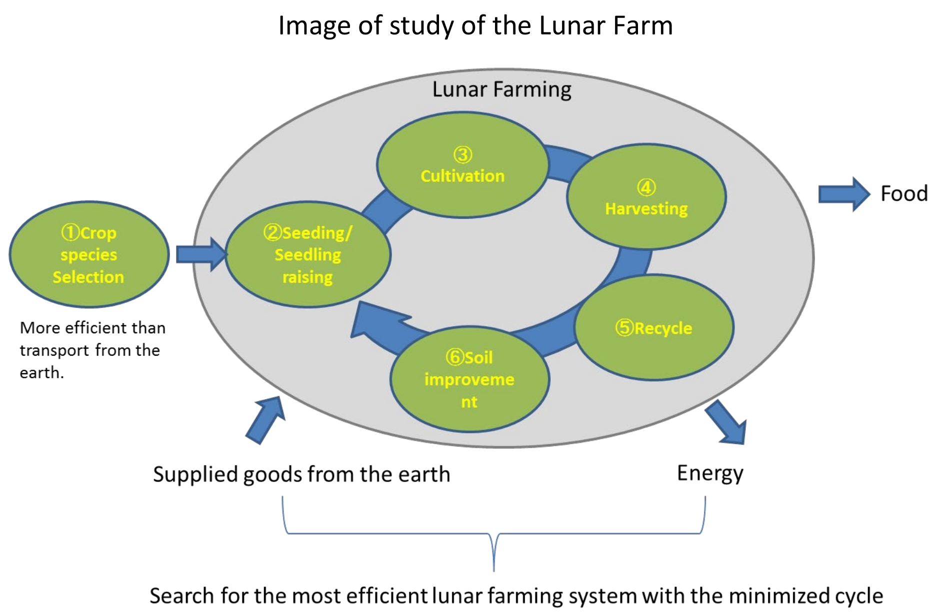

Figure 9.1 Image of study of the Lunar Farm (created by the Secretariat)

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

Figure 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.

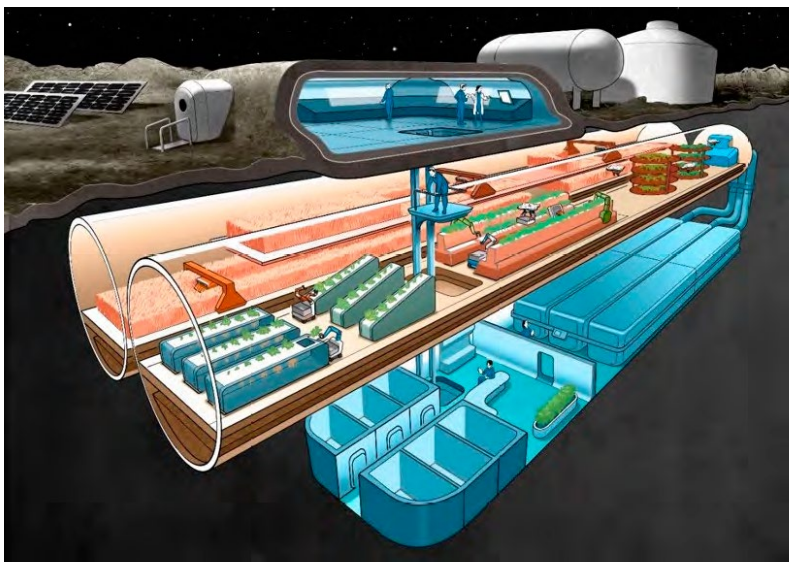

Fig. 9.2 Overall image of Lunar Farm (6-person scale) Figure 7.3 re-posted

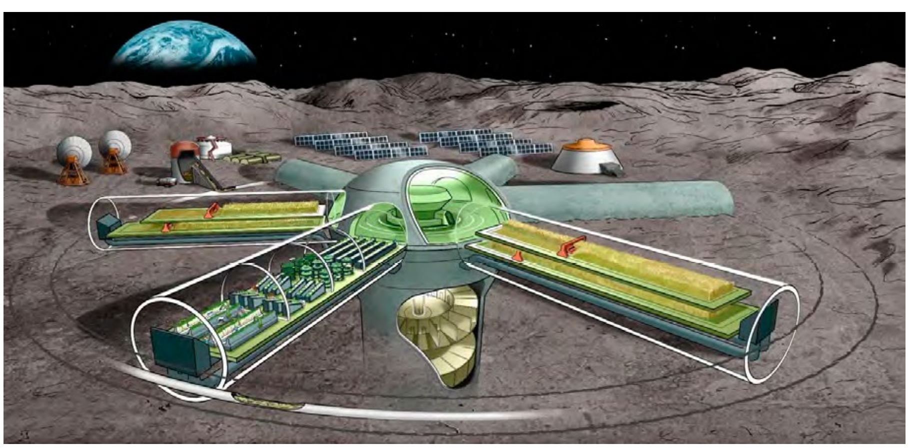

Fig. 9.3 Overall image of Lunar Farm (100-person scale)

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, CO_2, 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.

Tamagawa University LED farm

Tamagawa University FST laboratory

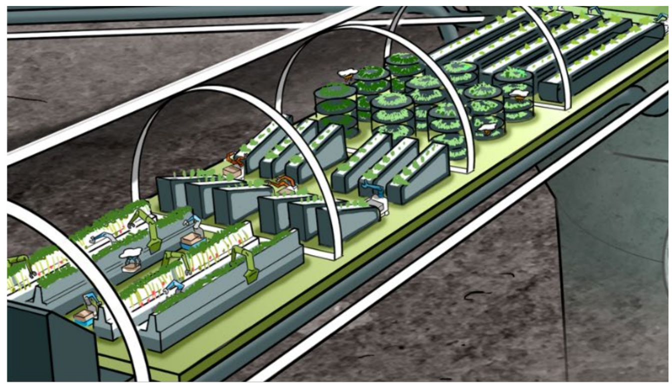

Image of cultivation on the lunar surface

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.

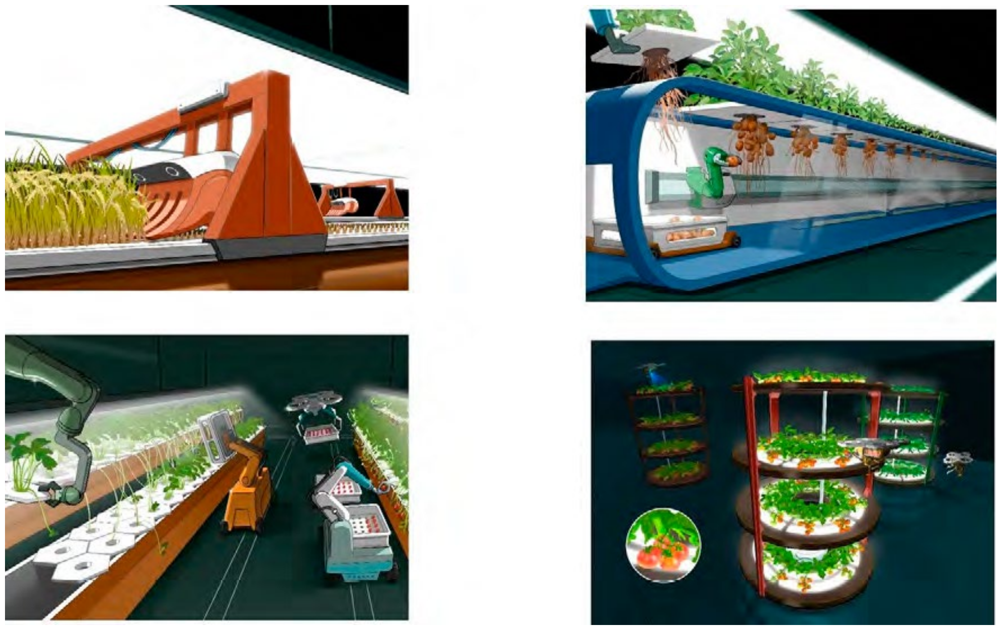

Fig. 9.5 Images of high efficiency plant training systems adaptable for robotic harvesting and managing operations.

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. Figure 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.

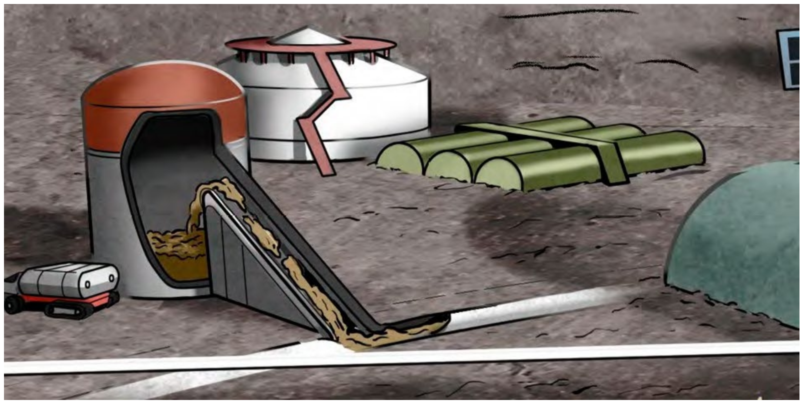

Fig. 9.6 Image of a substance circulation system

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

Based on the discussions of the Lunar Farm Concept Study Working Group, in 2017 and 2018 the Space Exploration Innovation Hub 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	Takenaka Corporation, Kirin Company, Limited, Chiba University, Tokyo University of Science

	an emergency using bag culture technology	
	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.

Acknowledgements

We would like to extend our deepest gratitude to each and every member of the Lunar Farming Concept Study Working Group, Mr. Kenji Kimura of the Cabinet Office, Professor Hiroshi Shimizu of the Kyoto University, Mr. Hideki Kanayama of CSP Japan K.K., Mr. Hidehiro Sasaki of JSP K.K. for providing the LACTIF medium, as well as Mr. Koji Kamino of Office K, Mr. Tiejun Zhao of Niiga Agro-Food University and many others for their immense collaborative efforts.

Header translation (alternating pages)

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- Japan Aerospace Exploration Agency Special Material JAXA-SP-19-001