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 themselves1). 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.

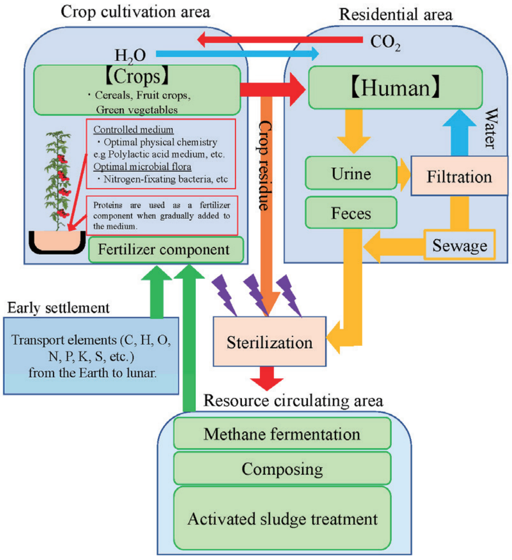


Fig. 6.1 Image of food production and resource recycling system on the lunar farm

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.

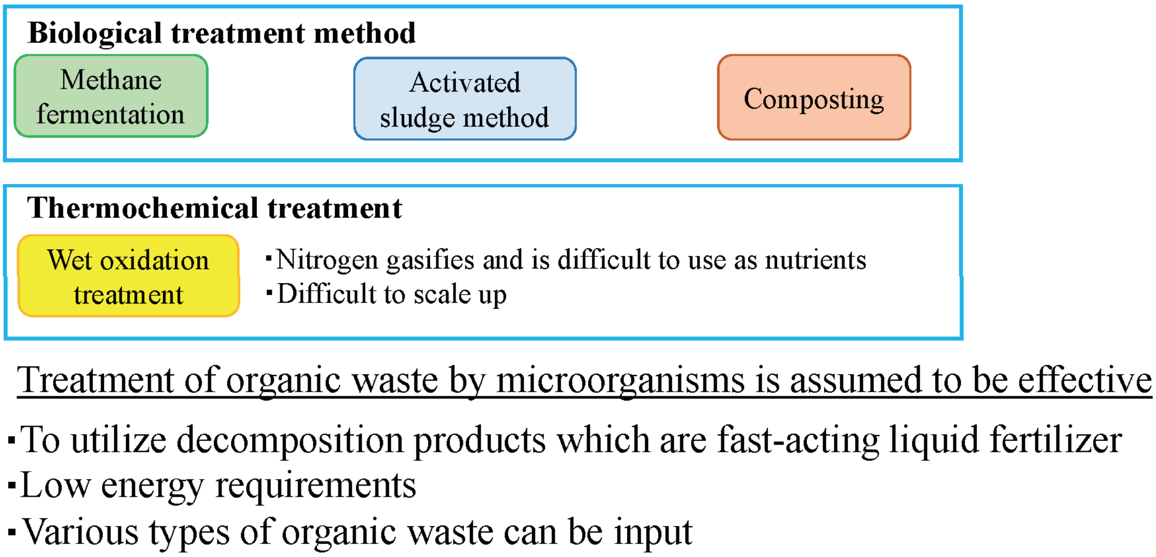
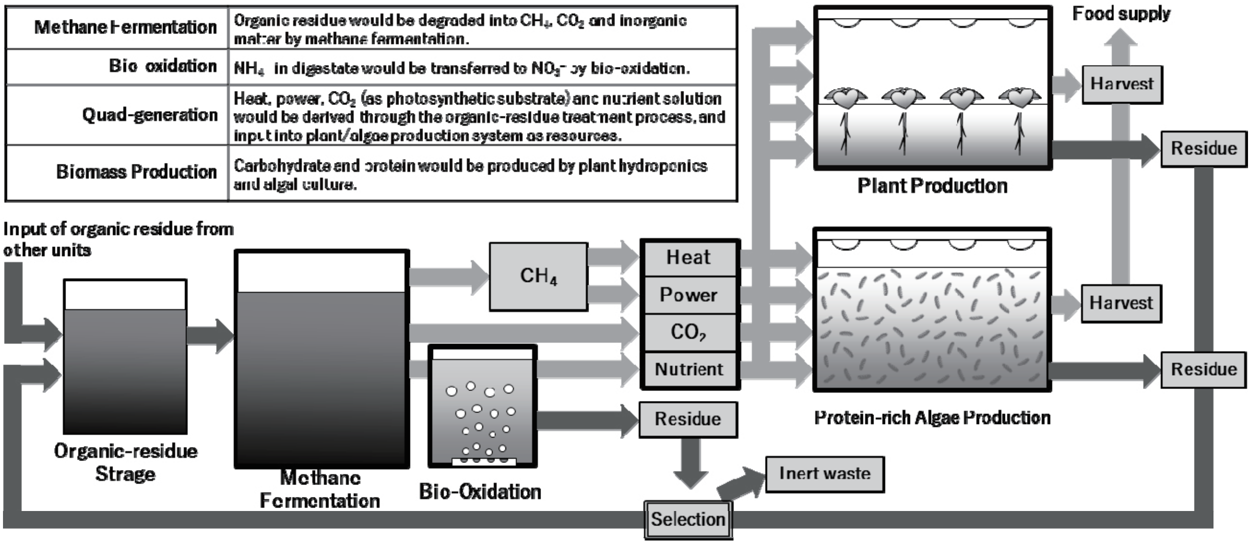


Fig. 6.2 Proposal of a Material Cycle Method Suitable for the Lunar Surface

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.



Methane Fermentation	Organic residue would be degraded into CH_4, CO_2 and inorganic matter by methane fermentation.
Bio oxidation	NH_4 in digestate would be transferred to NO_3^- by bio-oxidation.
Quad-generation	Heat, power, CO_2 (as photosynthetic substrate) and nutrient solution would be derived through the organic-residue treatment process, and input into plant/algae production system as resources.
Biomass Production	Carbohydrate and protein would be produced by plant hydroponics and algal culture.

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.

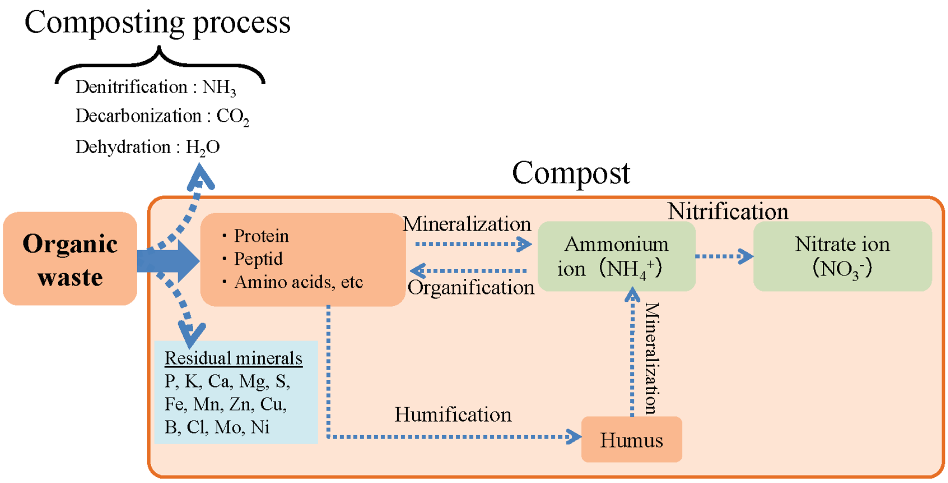
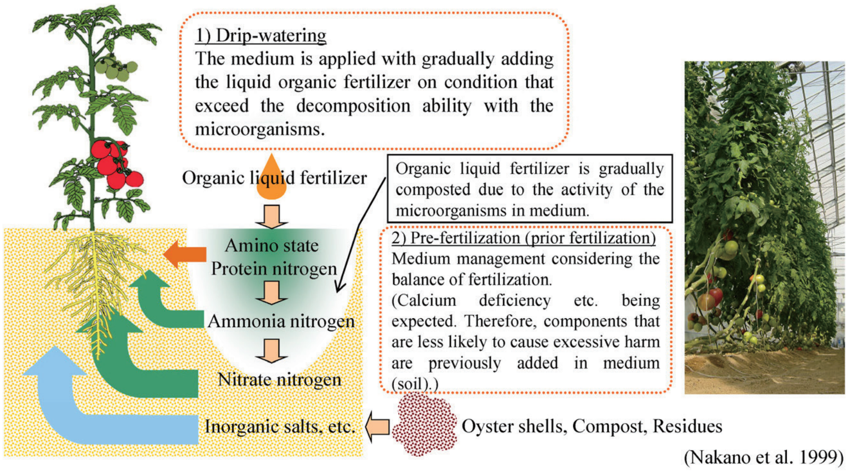


Fig. 6.4 Changes in composted households and nitrogen morphology

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.


1) Drip-watering
The medium is applied with gradually adding the liquid organic fertilizer on condition that exceed the decomposition ability with the microorganisms.

Organic liquid fertilizer is gradually composted due to the activity of the microorganisms in medium.

2) Pre-fertilization (prior fertilization)
Medium management considering the balance of fertilization.
(Calcium deficiency etc. being expected. Therefore, components that are less likely to cause excessive harm are previously added in medium (soil).)

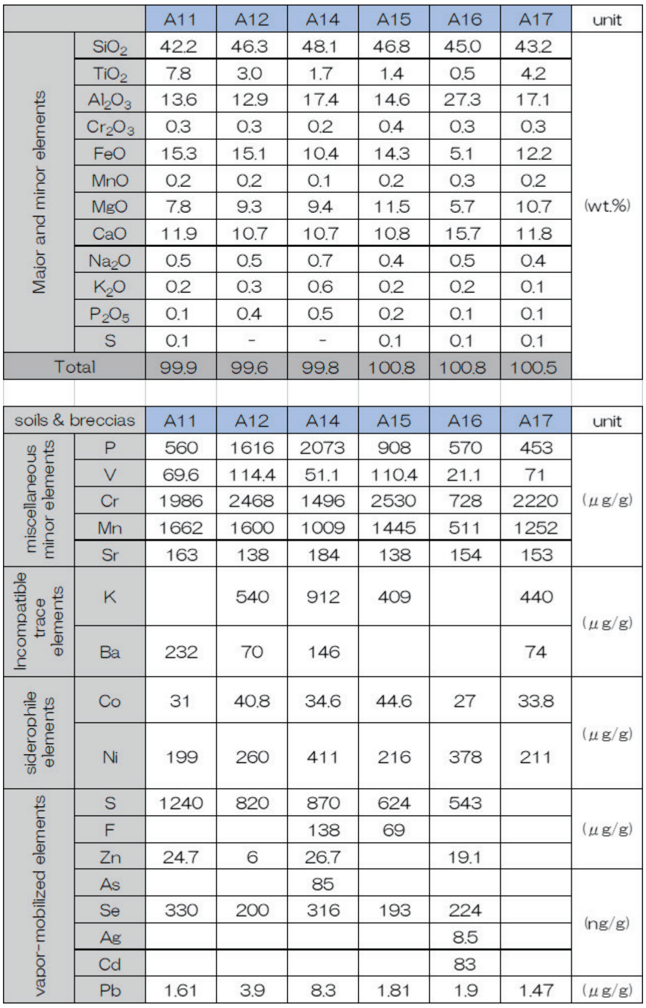
(Nakano et al. 1999)

Fig. 6. 5 Fertigation system

6.5 Use of lunar minerals as resources

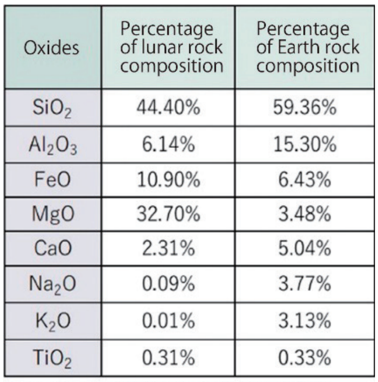
Since the elements that make up the lunar minerals (lunar regolith) are similar to the soil elements on the Earth [6)], in terms of concentrations of Ca, Mg, K, P, and trace elements (Tables 6.6 and 6.7), they can be used as a candidate source of crop nutrients. There are reports of tomato and wheat 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).

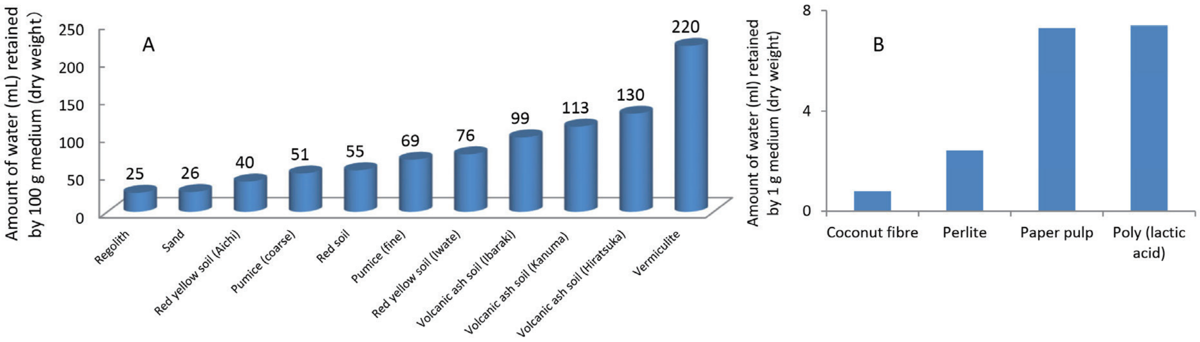


Fig. 6.6 Water-holding capacity of different media and soils

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.

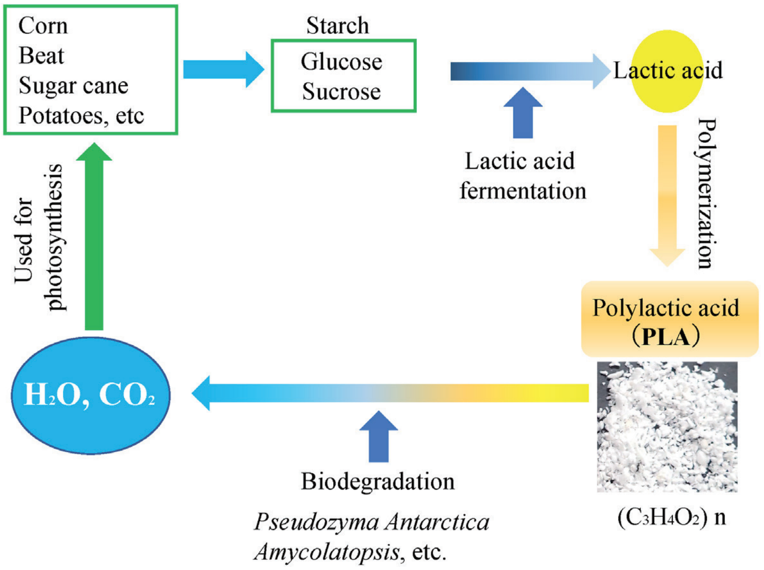


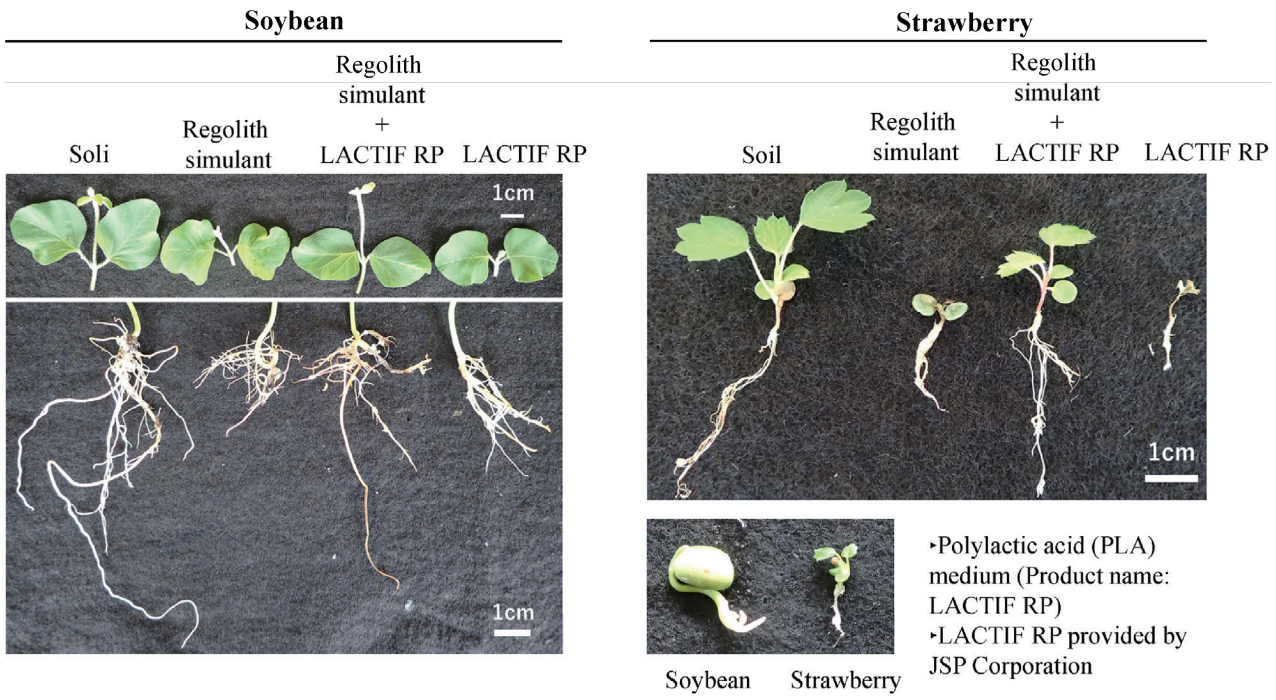
Fig. 6.7 Material cycle of polylactic acid

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.



‣Polylactic acid (PLA) medium (Product name: LACTIF RP)
‣LACTIF RP provided by JSP Corporation

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.

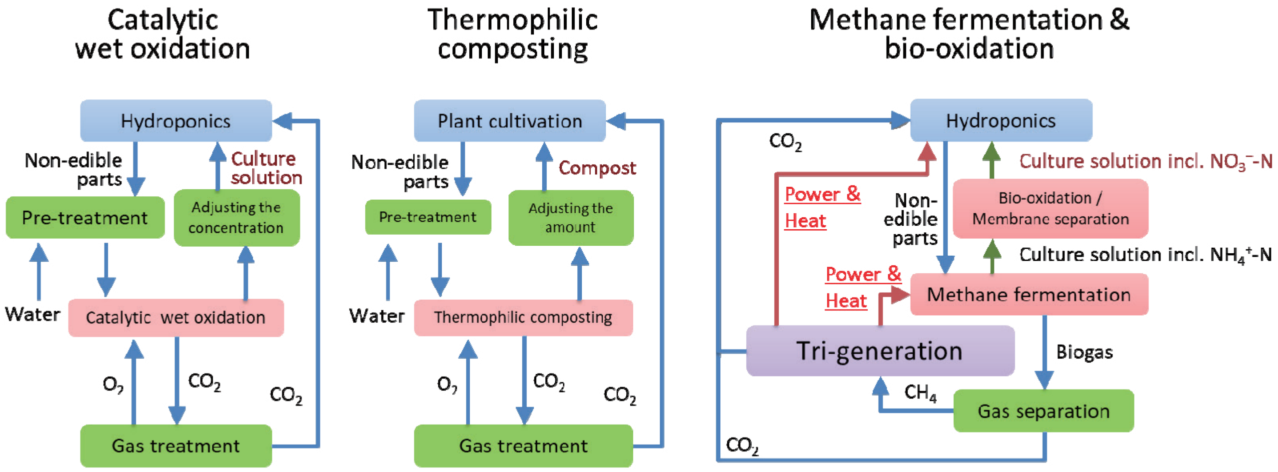
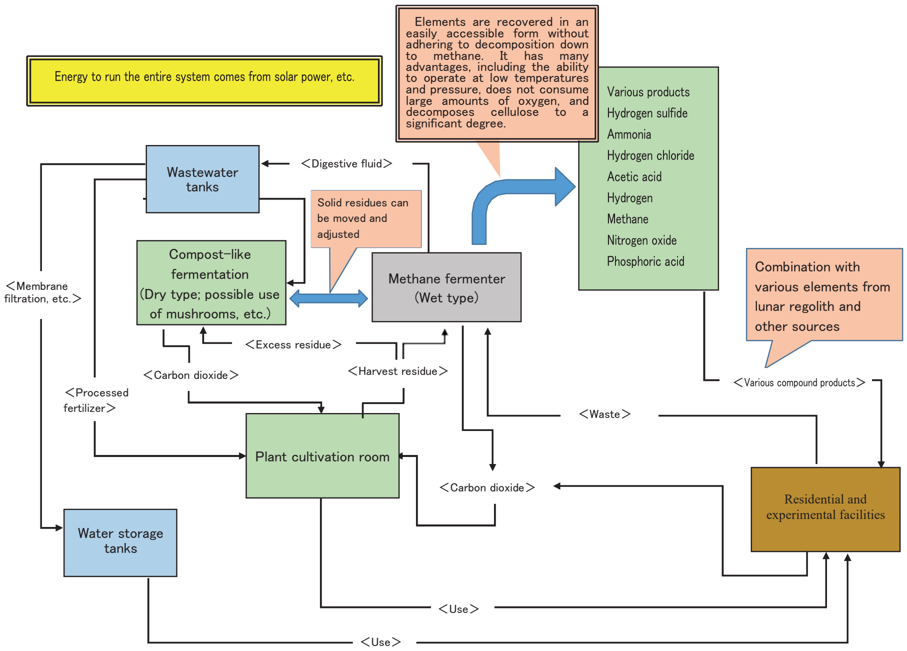


Fig. 6.9 Thermochemical and biochemical treatments for resource-recycling from plant residues in a closed system

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.


Energy to run the entire system comes from solar power, etc.

Elements are recovered in an easily accessible form without adhering to decomposition down to methane. It has many advantages, including the ability to operate at low temperatures and pressure, does not consume large amounts of oxygen, and decomposes cellulose to a significant degree.

Solid residues can be moved and adjusted

Combination with various elements from lunar regolith and other sources

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.

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