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六ヶ所村の閉鎖型生態系実験施設で行った閉鎖居住実験で試みた植物栽培による持続可能な食料生産

Sustainable food production based on plant cultivation attempted during closed habitation experiments conducted using Closed Ecology Experiment Facilities constructed in Rokkasho-village

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ABSTRACT

The Closed Ecology Experiment Facilities (CEEF) were installed to collect data for estimation of transfer of radio-nuclides from atmosphere to humans in the ecosystem. The first target among the radio-nuclides is ^{14}C. In order to validate function of material circulation in an experimental system constructed in the CEEF, circulation of air constituents, water and materials in waste was demonstrated connecting the Closed Plant Experiment Facility (CPEF) and the Closed Animal and Human habitation Experiment Facility (CAHEF) of the CEEF, since 2005 to 2007. The CPEF has a Plant Cultivation Module (PCM), which comprises of three plant chambers illuminated solely by artificial lighting, one plant chamber illuminated by both natural and artificial lighting, a space for preparation, and an airlock, and a physical/chemical material circulation system. The CAHEF has an Animal keeping and Human habitation Module (AHM), which is comprised of an animal room, a habitation room, a closed corridor, an airlock, and a physical/chemical material circulation system. During the material circulation experiments, two crews stayed in the CEEF being isolated from the outside. In these experiments, 23 crops including rice, soybean, peanut, and sugar beet were cultivated in the PCM, and two goats stayed in the AHM. Almost all of the food consumed by the crews and the feed to the goats (straw, leaf and bran of rice, leaf and stem of soybean, and leaf, stem and shell of peanut) were produced from crops in the PCM. The oxygen added to the air in the PCM by photosynthesis of crops was separated and supplied to the atmosphere in the AHM. Increased carbon dioxide in the AHM atmosphere by respiration of crews and goats was separated and supplied back to the air in the PCM. In addition to food production and circulation of air, water circulation was also conducted in the CEEF in 2006 and 2007. In addition to them, waste processing and circulation of materials from the waste in the CEEF were also conducted in 2007. Closed habitation experiments in 2005, each lasting one week, were conducted three times. In 2006, although the crews changed by week, 2-week habitation was conducted three times. In 2007, 1-week, 2-week (two times) and 4-week habitation were conducted. Data obtained in all of above experiments conducted in 2005-2007 will be also invaluable for examination and planning of human-in-loop systems necessary for independent long-term human living habitats such as lunar or Martian base.

Keywords: Food self-sufficiency, Water circulation, O_2 and CO_2 circulation, Hydroponics, Circulation of substances from waste decomposition.

1. INTRODUCTION

The Closed Ecology Experiment Facilities (CEEF, Figure 1) were installed to collect data for realistic estimation of transfer of radio-nuclides in the ecosystem. The first target among the radio-nuclides is ^{14}C. In order to simulate essential parts and their function of real ecosystems including humans, the CEEF are composed of the Closed Plant Experiment Facility (CPEF), the Closed Animal and Human habitation Experiment Facility (CAHEF) and the Closed Geo-Hydrosphere Experiment Facility (CGHEF) (Figure 2). For environmental control and material circulation, each facility has a material circulation system. In order to validate the function of material circulation in an experimental system, circulation of air constituents, water and materials in waste was demonstrated connecting the Closed Plant Experiment Facility (CPEF) and the Closed Animal and Human habitation Experiment Facility (CAHEF) of the CEEF, from 2005 to 2007. This material circulation system uses physical/chemical processes.

In this paper, we outline the material circulation – closed habitation experiments using the CEEF. Data obtained in these unique experiments will be also invaluable for examination and planning of human-in-loop systems necessary for independent long-term human living habitats such as lunar or Martian base.

2. OUTLINE OF AN EXPERIMENTAL SYSTEM

Basically, the experiments conducted in 2005-2007 shared a common experimental system. In the experimental system, 23 crops (Table 1) were cultivated sequentially, two goats were held, and two crews were inhabited (Table 2). The Plant Cultivation Module (PCM) and the material circulation system of the CPEF and the Animal holding and Human habitation Module (AHM) and the material circulation system of the CAHEF were all connected to each other as shown in Figure 3.

In all experiments, two goats stayed in the AHM. Almost all of the food consumed by the crews (82% in 2005 but more than 90% later) and the feed to the goats (straw, leaf and bran of rice, leaf and stem of soybean, and leaf, stem and shell of peanut) were produced from crops in the PCM. The oxygen added to the air in the PCM by photosynthesis of crops was separated and supplied to the air in the AHM. Increased carbon dioxide in the AHM atmosphere by respiration of crews and goats was separated and supplied back to the air in the PCM. In addition to food production and circulation of air, water circulation was also conducted in the CEEF in 2006 and 2007. In addition to them, waste processing and circulation of materials from the waste in the CEEF were also conducted in 2007.

3. OUTLINE OF RESULTS

3.1. Outline of Results from experiments conducted in 2005

Results on environmental control and material circulation from experiments conducted in 2005 are reported in Tako *et al*. (2008).

As planned, 1-week closed habitation experiments were conducted three times in 2005 to demonstrate circulation of O_2 and CO_2, and supply of food from crops cultivated in the CEEF. On a fresh weight basis, 82% of food was supplied from harvested crops in the 2nd and 3rd experiments. As for feed to the goats, all of it was produced in the PCM in the 2nd and 3rd experiments conducted in 2005. Table 3 summarizes environmental conditions in the AHM during the habitation experiments conducted in 2005. Figure 4 summarizes carbon flows determined in this work. The amount of CO_2 production in the AHM was 43-56% of that consumed in the PCM, and the amount of O_2 consumption in the AHM was 46-51% of that produced in the PCM. The surplus of O_2 and the shortage of CO_2 came from that almost part of waste was not processed in these habitation experiments. Estimated amount of carbon taken up by the crews was 64-92% of

that in the harvested edible part of the crops. Estimated amount of carbon taken up by goats was 36-53% of that in the harvested inedible part of the crops.

3.2. Outline of Results from experiments conducted in 2006

Results on environmental control and material circulation from experiments conducted in 2006 are reported in Tako *et al*. (2007 and 2008).

92-95% of the food consumed by the crews was produced by crops in the PCM, and 79% of the feed to the goats was produced in the PCM in these experiments. The average assimilation quotients (AQ = CO_2 /O_2) of rice, soybean and all crops, calculated from amounts [mol/d] of CO_2 injected to and O_2 separated from each plant chamber, were 0.95, 0.87 and 0.90, respectively. The AQs for rice and soybean were similar to the values calculated by following equation using the data of edible and inedible part production and nutritional content of these parts, assuming that AQs for carbohydrate & fiber, protein, and lipid are 1.0, 0.8, and 0.7, respectively.

AQ = [Edible biomass × {1.0 × (Ratio of carbohydrate & fiber) + 0.8 × Protein ratio + 0.7 × Lipid ratio} + Inedible biomass × {1.0 × (Ratio of carbohydrate & fiber) + 0.8 × Protein ratio + 0.7 × Lipid ratio}] / {Edible biomass × (1 - Ash ratio) + Inedible biomass × (1 - Ash ratio)}

The AQs calculated from above equation were 0.98 and 0.91 for rice and soybean, respectively. The average respiratory quotient (RQ = CO_2 /O_2) of crews + goats, calculated from amounts [mol/d] of CO_2 separated from and O_2 injected to the AHM was 0.86.

Water was also circulated in the CEEF in 2006, for the first time. The difference between water amounts of input to and output from the PCM was less than 0.5% of the input, and was comparable to amount of water withdrawn with harvested crops (Table 4). The difference between water amounts of input to and output from the AHM was approximately 9% of the input (Table 5). The difference could be attributed to withdrawn urine of the eco-nauts and water in form of steam withdrawn by pyrolysis of feces and urine of goats using outer air. In the 2006 experiment, only 500 L of waste nutrient solution was withdrawn for 38 weeks of a whole plant cultivation period including 18 weeks of harvesting period.

3.3. Outline of Results from experiments conducted in 2007

In 2007, 1-week, 2-week (two times) and 4-week habitation experiments were conducted. Waste processing in the last experiment (4-week habitation) in 2007 included six processes using air in the system; pyrolysis of urine of humans and feces and urine of goats, pyrolysis of inedible part of crops (except for feed for goats), incineration of carbonized human feces, incineration of carbonized mixture of goat feces and human urine, and incineration of carbonized inedible part of crops, in addition to pyrolysis of human feces in the AHM. CO_2 was recovered from all of these six processes. However, troubleshooting was done during November 11 – 22 and on December 1, then, pyrolysis of urine of humans and feces and urine of goats was done using outer air. During 10 days from December 2 to 11, when all of the waste was processed using air in the system, the amounts of CO_2 separated from the AHM atmosphere and sent to the CO_2 reservoir of the PCM (Figure 5), recovered from the waste decomposition processes (Figure 6) and injected to the PCM (Fig. 5) were 543 mol, 245 mol and 877 mol, respectively. It indicated that approximately 90% of CO_2 consumed by the crops was recovered from the AHM and the waste processing systems. On December 6, 38 moles of carbon were released out of the closed system during cleaning of the pyrolysis system for urine of humans and feces and urine of goats. This amount accounted to half of the amount of above-mentioned missing carbon.

4. CONCLUSIONS

During the material circulation experiments, two crews stayed in the CEEF being isolated from the outside. In these experiments, 23 crops were cultivated in the PCM, and two goats stayed in the AHM. Almost all of the food consumed by the crews and the feed to the goats were produced from crops in the PCM. The oxygen added to the air in the PCM by

photosynthesis of crops was separated and supplied to the air in the AHM. Increased carbon dioxide in the AHM atmosphere by respiration of crews and goats was separated and supplied back to the air in the PCM. In addition to food production and circulation of air, water circulation was also conducted in the CEEF in 2006 and 2007. In addition to them, waste processing and circulation of materials from the waste in the CEEF were also conducted in 2007. Closed habitation experiments in 2005, each lasting one week, were conducted three times. In 2006, although the crews changed by week, 2-week habitation was conducted three times. In 2007, 1-week, 2-week (two times) and 4-week habitation were conducted.

Data obtained in all of above experiments conducted from 2005 to 2007 will be also invaluable for examination and planning of human-in-loop systems necessary for independent long-term human living habitats such as lunar or Martian base.

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Figure 1. Overview of the Closed Ecology Experiment Facilities (CEEF).

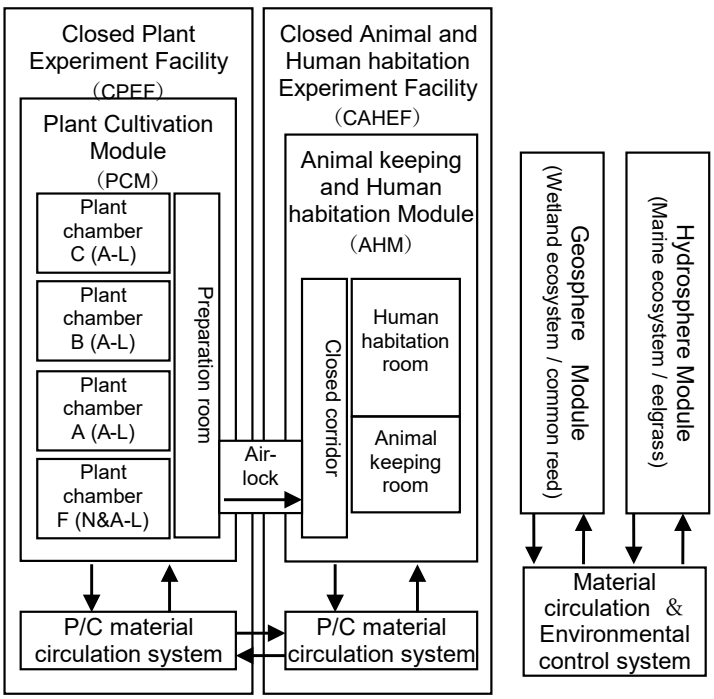

Figure 2. Overview of the CEEF.

Table 1. Cultivars (cv.) of crops cultivated sequentially in the CEEF (in case of 2006). PC: plant chamber(s), AAP: cultivation area after planting, PBP: cultivation period before planting, PAP: cultivation period after planting. *Seedlings of rice and soybean were grown in the PC-F before transplanting.The total growing area was 150 m^2 and 10.3 m^2 (a part of cultivation area in the PC-F) of this area was used for seedling growth.

Crop	PC	AAP [m^2]	PBP [day]	PAP [day]
Rice (*Oryza sativa* L. cv. Mutsu-homare)	A, B*	60.00	24	95
Soybean (*Glycine max* Merr. cv. Beer-friend)	C*	30.00	14	63
Peanut (*Arachis hypogea* L. cv. Satonoka)	F	30.00	0	140
Sugar beet (*Beta vulgaris* L. cv. Mono-homare)	F	5.00	14	126
White radish (*Raphanus sativus* L. cv. Sousa-hutori)	F	0.55	7	42
Turnip (*Brassica campestris* L. cv. Natsu-no-shou)	F	0.30	7	42
Cabbage (*Brassica oleracea* L. cv. Kinpu)	F	0.30	21	70
Pea (*Pisum sativum* L. cv. Sasabune)	F	0.55	7	70
French bean (*Phaseolus vulgaris* L. cv. Provider)	F	0.55	0	70
Onion (*Allium cepa* L. cv. Lucky)	F	0.55	49	91
Carrot (*Daucus carota* L. cv. Hitomi-gosun)	F	1.30	21	63
Chinese cabbage (*Brassica pekinensis* Rupr. cv. Eiou)	F	0.85	7	84
Tomato (*Lycopersicum esculentum* Mill. cv. Mini-carol)	F	1.50	21	84
Cucumber (*Cucumis sativus* L. cv. Mini-sala)	F	0.50	14	70
Sweet pepper (*Capsicum annuum* L. cv. Kyo-yutaka)	F	0.50	14	112
Shiso (*Pellira ocymoides* L. cv. Seikou)	F	0.50	28	70
Spinach (*Spinacia oleracea* L. cv. Altile)	F	2.50	0	35
Green onion (*Allium festulosum* L. cv. Tokyo-natsuguro-nigo)	F	0.30	14	56
Shungiku (*Chrysanthemum coronarium* L. cv. Sato-yutaka)	F	1.75	0	42
Komatsuna (*Brassica campestris* L.cv. Mizuki)	F	0.50	0	28
Lettuce (*Lactuca sativa* L. cv. Nanso-beni)	F	0.50	7	28
Mitsuba (*Cryptotaenia japonica* Hassk. cv. Kansai-mitsuba)	F	0.70	7	35
Leek (*Allium tuberosum* Rottler cv. Green-load)	F	0.50	21	84

Table 2. Confinement of crews and goats in the CEEF.

Experimental period in 2005	Sep 6-13	Sep 27-Oct 4	Oct 18-25			
Crews Number of goats	A&B 2	A&B 2	A&B 2			
Experimental period in 2006	Sep 5-12	Sep 12-19	Oct 10-17	Oct 17-24	Nov 7-14	Nov 14-21
Crews Number of goats	A&C 2	B&D 2	A&D 2	B&C 2	A&B 2	C&D 2
Experimental period in 2007	Aug 28-Sep 4	Sep 18-Oct 2	Oct 16-30	Oct 30-Nov 13	Nov 13-Dec 11	
Crews Number of goats	C&D 2	A&D 0	C&D 2	Absent 2	A&C 2	

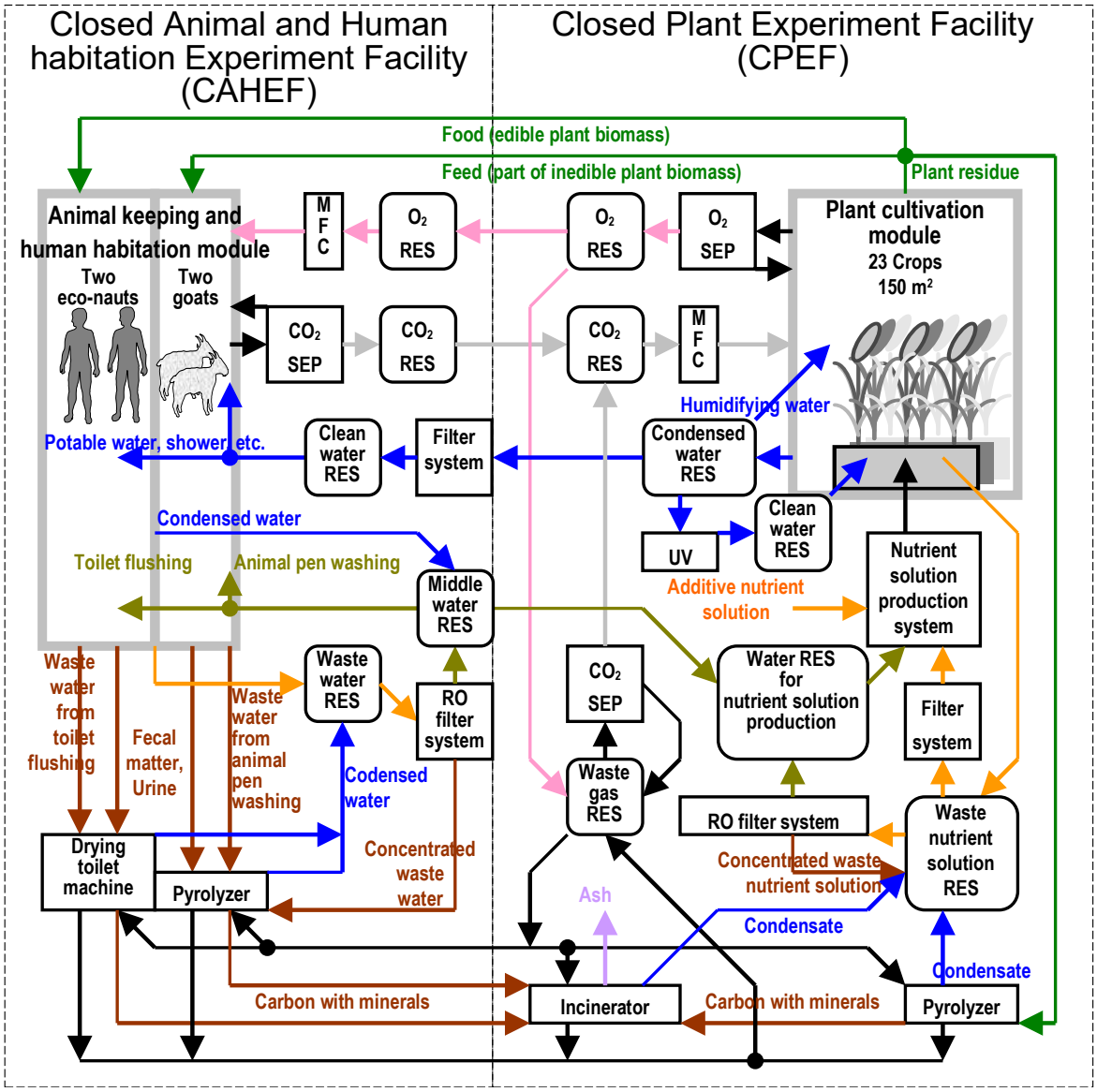

Figure 3. Material flows in the CEEF (in case of 2007). Transfer of food and feed from the CPEF to the CAHEF is conducted by two human inhabitants (eco-nauts). Circulation of air and water, and waste decomposition are conducted by physical/chemical material circulation systems. Plant cultivation module (PCM) comprises of three plant chambers (PC-A, B and C) illuminated solely by artificial lighting (each having room area of ~43 m^2, cultivation area of 30 m^2, and volume of ~146 m^3), one plant chamber (PC-F) illuminated by both natural and artificial lighting (having room area of ~65 m^2, cultivation area of 60 m^2, and volume of ~239 m^3), a space for preparation (having volume of ~332 m^3), and an airlock (~8 m^3). Animal keeping and human habitation module (AHM) is comprised of an animal keeping room (~54 m^3), a human habitation room (~123 m^3), a closed corridor (~163 m^3), and an airlock (~8 m^3). MFC: mass flow controller, RES: reservoir, RO: reverse osmosis, SEP: separator, UV: ultraviolet sterilization system.

Table 3. Environmental conditions in human habitation room and animal holding room of the AHM during the habitation experiments conducted in 2005.

Room	Experiment	Light period/dark period [h d^{-1}]	Temperature [°C]	Relative humidity [%]	CO_2 concentration [μL L^{-1}]	O_2 concentration [% (v/v)]
Human habitation room	1st experiment	16/8	24.8-25.5	37-55	1,477-3,676	20.1-20.6
	2nd experiment	16/8	24.9-25.4	37-51	1,472-3,492	20.0-20.8
	3rd experiment	16/8	24.9-25.3	37-52	1,832-3,514	20.1-20.3
Animal holding room	1st experiment	12/12	19.9-25.3	44-60	1,610-4,002	20.1-20.6
	2nd experiment	12/12	19.8-22.0	45-53	1,496-4,214	20.2-21.0
	3rd experiment	12/12	19.8-22.4	45-54	1,921-3,656	20.2-20.6

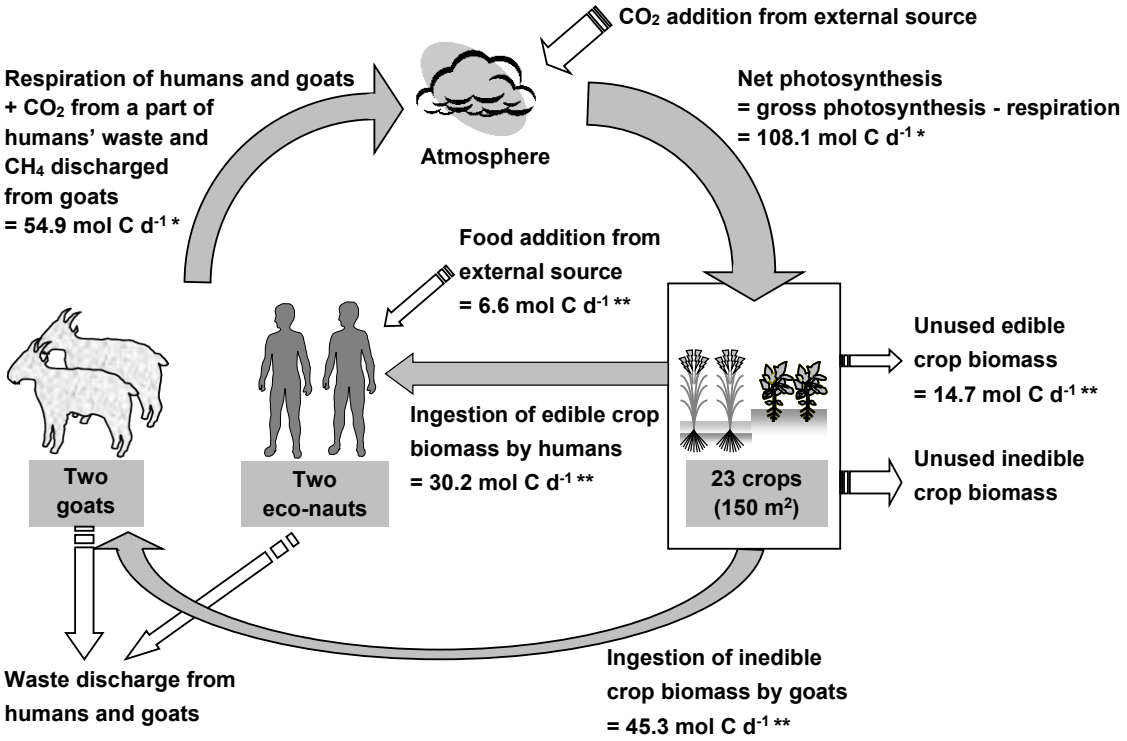

Figure 4. A summary of carbon flows in experiments conducted in 2005.
*: averages for three experiments in 2005, **: averages for the last two experiments in 2005.

Table 4. Water balance in the plant module (PM) in 2006 (Mean±SD for two weeks × three times).

Water supplied to the PM	Amount [L d^{-1}]
Replenished clean water	737±93
Supplied nutrient solution	1350±750
Water discharges from the PM	**Amount [L d^{-1}]**
Transpired water collected as condensate	679±22
Discharged nutrient solution	1400±720

Table 5. Water balance in the animal and human habitation module (AHM) in 2006. (Mean±SD for two weeks × three times).

Water supplied to the AHM	Amount [L d^{-1}]
Clean water	51.5±8.3
Middle water for toilet and pen washing	23.7±2.9
Water discharges from the AHM	**Amount [L d^{-1}]**
Reverse osmosis membrane processed water	56.3±17.8
Concentrated waste water	4.6±1.7
Condensed water	7.3±8.0

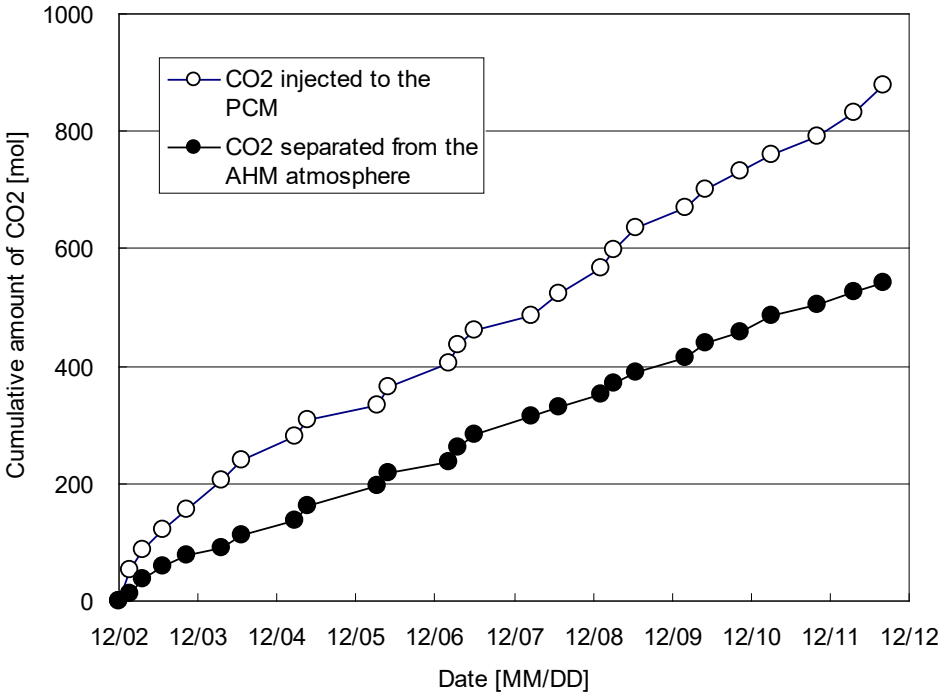

Figure 5. Cumulative amounts of CO_2 injected to the PCM and CO_2 separated from the AHM and sent to the CO_2 reservoir of the PCM, from December 2 to December 12, in the last experiment conducted in 2007.

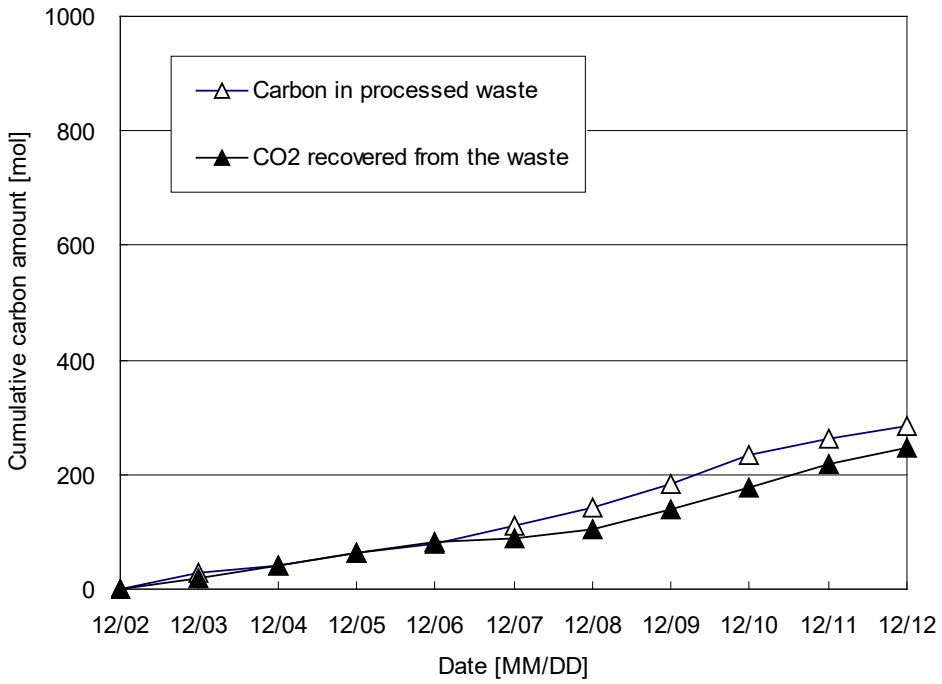

Figure 6. Cumulative amounts of carbon in processed waste and CO_2 recovered from the six processes of waste decomposition, from December 2 to December 12, in the last experiment conducted in 2007.

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