Conference of the Japan Society of Microgravity Application

OS2-3

微細藻類を用いた資源循環型食料生産の実用性検討
Potential for a resource-recycling food production system using microalgae

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1. Introduction

To minimize the supply of resources for a long-term human stay on the Moon, it is essential to establish a resource circulation system in a closed environment, especially for efficient food production with limited local resources. The use of plants and microalgae, photosynthetic microorganisms, in this circulation system is expected to efficiently retrieve resources from the waste. In particular, plants and microalgae fix CO_2 released into closed habitats by photosynthesis and generate oxygen. In addition, they utilize nitrogen and phosphorus in human domestic wastewater to grow and produce protein and various other nutrients. This paper describes the characteristics of representative microalgae that are expected to become resource-recycling foods on the Moon.

2. Role of Microalgae in Air Revitalization System

In the International Space Station (ISS), the CO_2 removal and O_2 generation are achieved through the water electrolysis ($2H_2O \rightarrow 2H_2 + O_2$) and the Sabatier reaction ($CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$) which are included in the Environmental Control and Life Support System (ECLSS). Although a part of hydrogen required in the Sabatier reaction is supplied by the hydrogen produced in the O_2 generating reaction, additional hydrogen is required to convert all of the CO_2 to O_2. The imbalance is required to be compensated by hydrogen supply from out of the closed environment or the capture and storage of excess CO_2 [1)].

A solution to this problem is to use photosynthetic organisms such as plants and algae to produce O_2 and food from CO_2 and nutrient-rich waste fluid. In particular, microalgae can be used for highly efficient food production because the space required for biomass production is less than that of crops, continuous harvesting is possible, and the whole harvested biomass is edible with less waste.

3. Potential of Microalgae as a Resource-Recycling Food

There are examples of microalgae culture tests conducted in closed isolation facilities in various countries and cyanobacteria (*Spirulina*) culture in the ISS[2)]. However, microalgae culture methods for low-gravity environments such as on the Moon have only just begun to be considered. The most suitable algae species and strains for use on the Moon have not been screened. Furthermore, the microalgae culture methods which are appropriate for the low-gravity environment have not been fully investigated[3]. Table 1 shows the characteristics of representative algae species that have been studied in space.

Table 1. Characteristics of representative algae

	Euglena gracilis (pH1.5-3.5)	*Chlorella vulgaris* (pH6.5-7.0)	*Arthrospira platensis* (pH8.5-11)
Advantages	1. Directly utilize ammonium contained in urine. 2. Low risk of contamination at pH3. 3. There is no growth inhibition by secreted components at high cell density. 4. High efficiency of genome editing.	1. Directly utilize urea and ammonium contained in urine. 2. There is no growth inhibition by secreted components at high cell density. 3. A successful culture on the ISS has been reported.	1. Low risk of contamination at pH9-11. 2. Can be eaten raw. 3. A successful culture on the ISS has been reported.
Disadvantages	1. Hydrogen sulfide is generated by the transition to oxygen-deficient conditions. 2. Accumulates storage polysaccharides not absorbed by humans.	1. Contaminates easily at pH 5-7 and is not suitable for raw consumption. 2. Cell walls reduce nutrient absorption.	1. Cannot directly utilize urea and ammonium contained in urine. 2. Growth is inhibited by the generation of free ammonia under alkaline conditions.

For example, the green algae *Chlorella* and *Chlamydomonas*, which proliferate rapidly and can utilize urea in urine as nitrogen sources, *Euglena*, which utilizes ammonium, and *Spirulina*, which utilizes nitric acid obtained from the nitrification reaction of plant residues are candidates for the production on the moon. *Euglena* is especially nutritious and has high potential as food. It was reported that *Euglena* contains 30~50% protein in dry weight, and its amino acid value is 88, higher than *Spirulina* and *Chlorella*[4]. Furthermore, *Euglena* contains many minerals and can synthesize all vitamins except vitamins B_1 and B_{12}. Utilizing the potential of microalgae, a highly-efficient food production system in a closed system can contribute to air revitalization and supply of nutrients that are deficient in vegetables and other plants.

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