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宇宙農場における資源循環の重要性と課題について

Importance and Challenges of Resource Circulation in Space Farming

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1. Introduction

In order to sustain life in a closed system away from the earth for a long period of time, it is necessary to establish a technology to produce food sustainably by using the materials in the system in a cyclical manner. Since inorganic resources are required for food production, resource recycling technology is required to collect organic materials that are no longer needed in the system and to efficiently convert them into inorganic resources.

In a small closed system such as a spacecraft, it is difficult to slowly circulate materials in the presence of a large spatial and temporal buffer like on Earth. Inevitably, resource circulation units need to be space-saving and have fast material conversion reactions with high resource conversion rates. However, it is becoming clear that such resource recycling is limited by a variety of factors. In this presentation, we focus on the resource recycling unit in particular, and summarize the chemical and biological factors that limit resource recycling food production in a closed system, and discuss methods to overcome or mitigate these factors.

2. Overview of resource-circulating food production system

Food production in a closed system is mainly based on organic matter synthesis by light energy-utilizing autotrophs. Higher plants and microalgae are assumed to be the candidate organisms, and food production is carried out under artificial light irradiation where the physical environment such as temperature and humidity is controlled. The plants will be cultivated in a nutrient solution with high absorption efficiency, and the nutrient source will be supplied through the culture medium. The culture medium contains a sufficient amount of inorganic substances necessary for growth.

The inorganic resources in the culture medium are obtained by decomposing the inedible parts of plants and organic matter such as excrement, which are no longer needed in the closed system, in the resource recycling unit. Some inorganic resources, such as nitrogen, have multiple forms, such as ammonium and nitrate forms. For such substances, it is important to decompose them in a form that can be absorbed by plants and microalgae. In the mineralization process, it is important to keep the resource recovery efficiency as high as possible so that some of the resource components do not dissipate as gas or accumulate as precipitation in the resource circulation unit. In addition, a variety of plant species are expected to be the main food source in the closed system. It is also important that inorganic substances to be recovered as resources are dissolved in the liquid phase, since hydroponic cultivation with simultaneous irrigation and fertilization using culture media is expected as a plant cultivation method.

3. Thermochemical and biochemical treatment

There are two methods of mineralizing organic matter: thermochemical and biochemical. In the Closed Ecosystem Experimental Facility (CEEF), which has been under construction since 1994 in Rokkasho Village, Aomori Prefecture, a catalytic wet oxidation process has been attempted in combination with this method (Table 1). Although the decomposition time is shorter than that of the biochemical treatment described below, there is a risk in maintaining the equipment that can withstand high temperature and high-pressure treatment and the catalyst that is prone to degradation. Another problem is that phosphorus and iron are difficult to dissolve.

Biochemical treatment includes composting and bio-oxidation, which utilize mainly aerobic microorganisms, and methane fermentation, which utilizes anaerobic microorganisms. Although each of them has different characteristics, they are all widely used as waste treatment technologies on the ground. As resource recycling technologies in closed systems, composting and bio-oxidation require short reaction times, but the concentration of organic matter cannot be very high. Methane fermentation can be used to treat a wide variety of organic materials and high concentrations of organic matter, but the reaction time is long.

In biochemical treatment, there is a difference in the form of inorganic matter produced depending on the method. In composting, the main product is solids, which contain inorganic matter. In the latter stage of the food production unit, inorganic matter is supplied by the culture medium, so it is necessary to extract the inorganic matter contained in the compost into the medium by some means. In the case of bio-oxidation and methane fermentation, the inorganic matter is dissolved in the liquid, so the liquid containing the inorganic matter can be obtained by filtering through a hollow fiber membrane to remove microorganisms. However, the liquid obtained from biological oxidation is weakly acidic and the form of inorganic nitrogen is nitrate-nitrogen, while the liquid from methane fermentation is weakly alkaline and ammonium nitrogen. The liquid obtained from biological oxidation is more suitable as a culture medium for plant nutrient cultivation.

Table. 1 Suitability as a culture solution in fertilization for plant production or algae culture in space farming.

	Thermophilic composting [1]	Catalytic wet oxidation [2]	Methane fermentation [3]	Methane fermentation & biological oxidation [4]
Solid or liquid	Solid	Liquid	Liquid	Liquid
Inorganic nitrogen form	Ammonia, ammonium, nitrate	High nitrate	High ammonium	Nitrate and ammonium
Phosphate	○	×	△	○
Potassium	○	△	○	○

4. Implementation of resource recycling using microbial functions and challenges

Figure 1 shows a resource recycling unit that utilizes the functions of anaerobic and aerobic microorganisms that the authors have been developing. Organic wastes collected in the storage unit are fermented and decomposed into inorganic form in the methane fermentation unit consisting of anaerobic microorganisms. In the subsequent biological oxidation unit, ammonia nitrogen is converted to nitrate nitrogen by nitrifying bacteria. After that, the solid-liquid phase is separated by a membrane, and the liquid phase is fed into the culture medium storage tank, while the solid phase is fed back into the methane fermentation tank as residue.

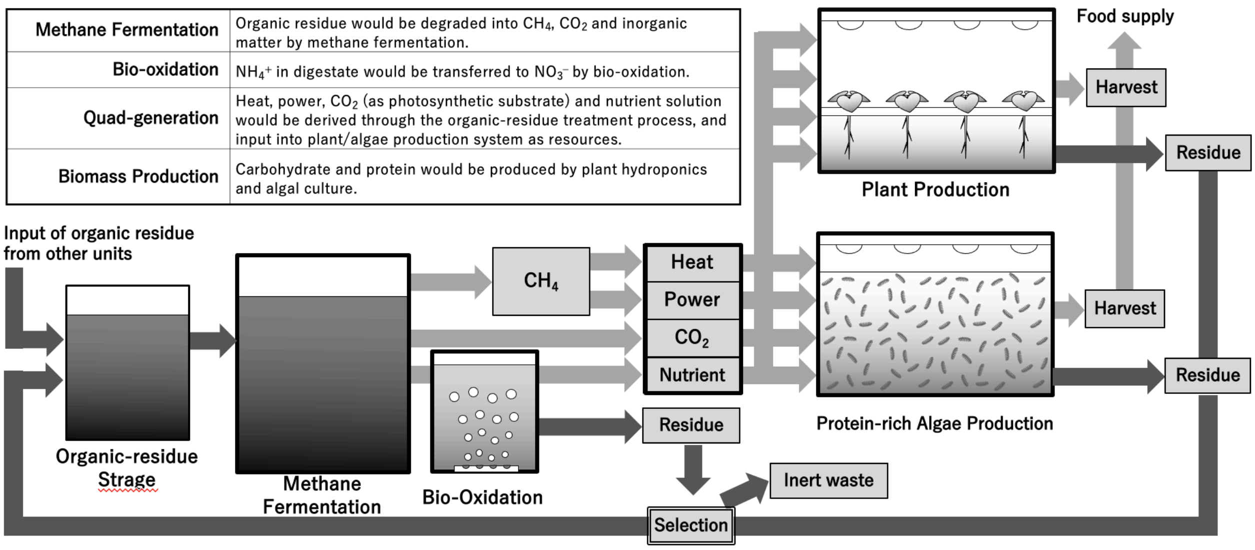

Fig. 1 Quad-generative waste-to-food system for application to CELSS.

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4.1 Methane Fermentation

Methane fermentation is a decomposition reaction by a consortium of anaerobic microorganisms, such as acid-producing bacteria and methanogenic archaea, through the cooperation of many microorganisms. The decomposition reaction of input organic matter ($C_nH_XO_YN_Z$) is represented by the following equation.

$$\mathrm{C}_n\mathrm{H}_X\mathrm{O}_Y\mathrm{N}_Z + \frac{1}{4}(4n - X + 2Y + 7Z)\mathrm{H_2O} \rightarrow \frac{1}{8}(4n + X - 2Y + 3Z)\mathrm{CH_4} + \frac{1}{8}(4n - X + 2Y - 5Z)\mathrm{CO_2} + Z\mathrm{NH_4}^- + Z\mathrm{HCO_3}^-$$

Methane fermentation can process a wide range of organic matter including carbohydrates, proteins and lipids with high organic load. The digestate containing inorganic matter produced after the methane fermentation process is in the liquid phase, as is the culture medium used in hydroponics.

The mineralized form of nitrogen compounds is the ammonium form, and it cannot be used as a culture medium for plants whose main nitrogen form is the nitrate form. The ammonium form of nitrogen, however, can be converted to nitric acid by biological oxidation treatment using the functions of nitrate bacteria.

The pH of the methane fermentation solution is around 7 to 8.5, and the higher the pH, the more multivalent metal ions such as calcium and magnesium combine with phosphate and ammonium ions to form precipitates. The higher the pH, the more precipitates will form, and the less likely they are to be fed to subsequent processes, thus reducing the circulation rate of the material. The solution to the problem of sedimentation is to keep the pH as low as possible during methane fermentation. However, if the pH drops below 6.5, the fermentation will fail due to acidification, so it is necessary to maintain the pH higher than that. The latter stage of the biological oxidation process is acidic, and the precipitates produced at high pH are easily redissolved. Therefore, it would be effective to make some engineering devices so that the precipitates generated in the methane fermentation can be supplied to the subsequent process.

4.2 Biological Oxidation

Many aerobic microorganisms exist in the reactor for biological oxidation. The nitrification reaction, which is the main reaction, is carried out by nitrite and nitrate bacteria groups. Nitrifying bacteria group nitrifies the digestive juice produced by methane fermentation, which converts the nitrogen form from ammonia form to nitrate form. In this process, the pH can be shifted to the acidic range suitable for hydroponics. In addition, the quality and quantity of inorganic nutrients in the culture medium are improved because the precipitates produced by methane fermentation are dissolved again as the pH decreases.

If the digestate produced by methane fermentation is fed directly, the organic load is too high, causing inhibition of the reaction. In addition, when the pH of the digestate is high, some gaseous ammonia is contained, and if this is highly concentrated, it becomes a factor that inhibits the reaction of microorganisms. To avoid these problems, it is necessary to dilute the digestate and feed it into the biological oxidation tank.

In the nitric acid conversion reaction, the pH of the digested solution decreases with the production of nitric acid, and may eventually reach less than pH 4. In this case, the acidity of the solution is too high and it is not suitable as a culture medium for plant nutrient cultivation. Therefore, it is necessary to maintain the pH of the bio-oxidation tank at a weak acid.

In the existing technology, the pH of the biological oxidation tank is adjusted by feeding alkaline agents. In the right-hand equation of the nitrite formation reaction described above, two protons are generated, which contribute to lowering the pH, so a substance that consumes these protons can be added.

Unlike above ground, in a closed system, the process must be composed only of materials from circulating resources; in case of pH adjustment, alkaline materials must be generated separately by some means. Bicarbonate ions are included in the right-hand equation of the methane fermentation reaction described above, and if the biological oxidation tank contains an abundance of bicarbonate ions as a pH buffer, the pH fluctuation will be small. Since the amount of bicarbonate depends on the composition ratio of the input organic matter, if the composition of the organic matter input to the methane fermentation tank may be adjusted, the alkalinity of the subsequent biological oxidation tank may be maintained through this.

5. Conclusion

As described above, most of the existing methods have some limitations as well as advantages. However, it is hoped that these limitations can be minimized by designing the process using a combination of biological and engineering knowledge. In the future, further accumulation of knowledge and technological innovation through interdisciplinary research will be important.

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