Conceptual design of Anaerobic Digestion Plant for Marine Biomass Utilization

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Marine biomass such as seaweed and fishery waste is a potential energy source although it has not yet been practically utilized. This study focuses on anaerobic digestion for the utilization of various organic wastes as energy resources. We introduce marine biomass utilization system, which consists of biomass transportation, anaerobic digestion, and energy conversion, and propose three scenarios varying with waste biomass supplier. The purpose of this paper is to understand digestion characteristics of seaweed, fishery and vegetable waste, and tamarind, which is raw material for the chemical product and the residue in the production process, through batch-processing experiments. Also we investigate feasibility from the economic and environmental viewpoints. The results indicate that each biomass has each digestion characteristics and especially seaweed, fishery, and tamarind have high carbon recovery rate. Among three scenarios, the case including tamarind is the most feasible. Anaerobic digestion can replace energy and products derived from fossil fuels as more environmentally friendly alternatives, however, it has big obstacle in the economically feasible operation.

Kew Words
Seaweed, Food waste, Anaerobic digestion

1. Introduction

Ulva species called sea lettuce, a kind of seaweed, often propagates explosively and piles up in shallows. Such phenomenon has been reported in both the Japanese enclosed sea and world eutrophic shallow water areas, and is called “green tide.” This is because nutrient level in an enclosed sea near big industrial cities is very high since the pollution load is much higher than the natural purification capacities. Since such seaweeds are either burned or buried in the ground after harvest, they have been regarded as waste and not as energy resources.

Anaerobic digestion has attracted attention as one of the techniques to convert seaweed to usable energy though it has not been widely used in Japan. One of the reasons is that biomass yield seasonally changes with causing unstable supply. In this study, we include food waste, which can be consistently obtained all year round. We conduct hearing survey to develop database of available amount of biomass around Osaka Bay. The purpose of this study is to develop the concept of the anaerobic digestion system in Osaka Bay. Firstly, we conduct batch-processing experiments to understand digestion characteristics of available biomass in Osaka Bay. Secondly, we assess the feasibility of the proposed anaerobic digestion system from the economic and environmental viewpoints.

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2. Marine Biomass Utilization System

In many of Japan’s eutrophic shallow water areas, green tide, caused by the bloom of green algae, occurs in the summer season. Dead green algae then accumulate at the bottom of the sea and on beaches, resulting in large amounts of debris and damaging the benthic ecosystem. By convention, the dead algae are burned in a combustion plant with the consequent consumption of fossil fuels. However, the green tide species, particularly Ulva sp., have a rapid growth rate and therefore effectively fix carbon and nutrients. If they can be used before they die and accumulate on the sea floor, there could be a reduction in the nutrient concentration of seawater and a reduction in the supplementary fuels required for combustion. Eutrophication occurs as a result of organic matter and nutrients from human activities building up in enclosed waters. The utilization of biomass from the green tide species can therefore be regarded as a recycling process for CNP waste.

The concept of a biomass utilization system based on CNP recycling for marine biomass is illustrated in Fig. 1. Marine biomass produced by the green tide species is harvested before accumulation and decomposition. Seaweeds (Cladophora sp.) cultivated in the system absorb carbon and nutrients and can prevent eutrophication and the resulting red and blue tides. Therefore, the marine biomass utilization system is important from the viewpoint of the material cycle between land and sea. This study focuses on anaerobic digestion in the marine biomass utilization system.

3. Available Amount of Biomass around Osaka Bay

Suppliers selected for the study were interviewed and they provided details of the type of biomass and the annual weight (see Table 1). All sites except the fishing port and the seaweed culture are located in Sakai in Osaka. The fishing port is located in Izumisano near Kansai International Airport. The seaweed culture is a private site. There are five types of biomass: seaweed (Ulva sp.), dry seaweed (Nori), vegetable (mainly lettuce or cabbage), fishery waste, and tamarind residue. Tamarind (Tamarindus indica) is a tree grown in India etc. and its seeds are refined to be tamarind seed gum, which is used as food additive. We found that tamarind residue, which is the waste in the tamarind refining process, has been incinerated. Tamarind residue is a good candidate because it is supplied stably and produced in the factory in Sakai. Seaweed from green tide is available from spring to fall and varies from year to year; therefore seasonal change of seaweed yields is not appropriate for the stable plant operation. On the other hand, there are stable supply from vegetable-processing factory, supermarkets, supermarket food factory, whole fish market, and chemical product factory, making it possible for the plant to operate stably. It is important to consider characteristics of both biomass and digestion characteristics to develop a concept of anaerobic digestion plant.

4. Anaerobic Digestion

Anaerobic digestion is a biological conversion process, in which organic matter is converted to biogas (consisting mainly of methane and carbon dioxide) as a product. The performance of anaerobic digestion depends on largely on the types of organic matter; therefore it is important to understand the anaerobic digestion characteristics of the targeted biomass for the efficient operation. The purpose of the experiments is to understand the fundamental characteristics of possible biomass shown in Table 1. Table 2 summarizes the chemical characteristics of the biomass. Seaweed and vegetable waste has more water content.
Fishery waste and tamarind contain more carbon than the others. With regard to C/N ratio, dry seaweed, fishery waste, and tamarind have low C/N, indicating that they contain more protein.

4.1 Batch-processing experiments

All biomass was in a slurry state with an electric blender before the experiments. A sealed 100 mL glass bottle filled with sewage sludge (60 mL) was used as a digester. The bottle was tightly stoppered with rubber stoppers and was placed in a temperature controlled chamber at 35 °C. It was stirred at 130 rpm with a magnetic stirrer. The rate of addition of organic load was 3.0 kg-dry/m³. The volume of the biogas was measured with a 10 mL syringe. Gas analyses (N₂, CH₄, CO₂) were carried out by gas chromatography (SHIMADU, GC-8A) using a thermal conductivity detector and a 2.0 × 2.0 mm stainless-steel column packed with Porapak Q with helium as a carrier gas.

4.2 Digestion characteristics

Figs. 2 and 3 show actual methane production rate and methane production per unit weight of biomass input, respectively. From the viewpoint of production rate, fishery and vegetable waste have a rapid growth in the first three days and fishery waste continue to increase reaching the maximum at day 14. Fishery and vegetable waste drop significantly after reaching the maximum production rate. Tamarind has a steady production until day 9 and gradually goes down. Seaweed has smaller peak than dry seaweed (Nori). Among five biomass, dry seaweed showed the most efficient production rate regarding to total biomass input, while seaweed and vegetable waste showed the lowest (see Fig. 3). The reason is that dry seaweed has much less water content than the one of seaweed and vegetable. Daily biomass weight is important to determine the volume of digestion tank; therefore careful attention about mixture of biomass input is required to design compact and efficient anaerobic digestion plant.

Table 3 summarizes total methane yield per unit weight of biomass and that per unit weight of carbon in the biomass, and carbon recovery rate, which is defined by the ratio of carbon in produced methane to carbon in the biomass. The results indicate that seaweed, fishery, and tamarind can efficiently convert carbon in biomass to the carbon in methane, however, water content of seaweed can be an obstacle to the compact design of the digestion plant. The other concern about dry seaweed, fishery, and tamarind is that their C/N ratio is lower than the others, meaning that they contain more nitrogen. Low C/N biomass has a risk to cause the inhibition by ammonia. Even though Tamarind and dry seaweed can cause ammonia inhibition, they are promising biomass from the aspect of the methane.

| Biomass                  | Total Solids [%] | TOC [mgC/g-dry] | C/N |
|-------------------------|-----------------|-----------------|-----|
| Seaweed (Cladophora sp.)| 10              | 174             | 14.5|
| Dry seaweed (Nori)      | 90              | 417             | 6.7 |
| Fishery waste           | 27              | 497             | 6.4 |
| Vegetable waste         | 8               | 388             | 18.8|
| Tamarind                | 31              | 461             | 7.2 |

| Biomass                  | Methane [mL/N/g-wet] | Methane [mL/N/g-C] | Carbon recovery rate |
|-------------------------|----------------------|-------------------|----------------------|
| Seaweed (Cladophora sp.)| 20                   | 1150              | 0.62                 |
| Dry seaweed (Nori)      | 254                  | 676               | 0.36                 |
| Fishery                 | 154                  | 1145              | 0.61                 |
| Vegetable               | 20                   | 639               | 0.34                 |
| Tamarind                | 121                  | 1082              | 0.58                 |
production rate and the yields.

5. Feasibility Study

5.1 System Description

The anaerobic digestion system analyzed in this paper is schematically presented in Fig. 4. Marine biomass, including seaweed and fishery waste, and food wastes are pretreated to produce a slurry. The methane gas produced is converted to electricity and heat in a cogeneration system. Part of this energy is returned and used in the anaerobic digestion plant, and surplus electricity and heat are supplied to the public bath in the commercial facility, which also has a movie theatre and bowling alley. The digestive sludge produced as a by-product of the digestion process can be used as liquid fertilizer. The proposed system is therefore a low-carbon system of energy production that also contributes by improving the benthic ecosystem. We investigate three scenarios dividing biomass into two characteristics: stable supply and seasonal change as shown in Table 4. We assume that the mixture of biomass does not affect each methane yields following the experimental results in Table 3. Fig. 5 shows maximum daily weight of biomass and the composition in a year: Case 1 for 5.7 t, Case 2 for 5.7 t, and Case 3 for 6.6 t. We assume that cultivated seaweeds (Cladophora sp.) are 52 t/y.

5.2 Economic Feasibility

We assume that the plant construction cost can be described by an approximated curve, based on five existing plants that contain municipal waste, agricultural food waste, and fishery waste and whose daily processed biomass is up to 25 t:

\[ y = 348.5x^{-0.279} \]  

where \( y \) is the construction cost per daily biomass weight (10^6 JPY/t), and \( x \) is the maximum daily biomass weight in a year (t/d). The maximum daily biomass weight applied to Eq. 1 includes dilution water and is the biomass input in summer because harvested seaweeds are the most in summer. We assume that half of the construction cost is paid in advance. Costs during the operation, OC, consist of the costs generated by collecting seaweed (CS) and food waste (CF) and the costs of the plant operation (CP) as follows:

\[ OC = CS + CF + CP \]  

where CS is the labor cost of harvesting seaweed and seaweed net. The labor cost is calculated based on the number of employees over a year. CF consists of the fuel cost (light oil) and the labor cost of collecting food waste. CP consists of maintenance, the labor cost of the operation of the plant, depreciation, and interest. The cost assumptions are summarized in Table 5. Japan Statistical Year Book was referred to for labor cost.

The plant receives revenue by selling electricity and heat generated from biogas. We assume that electricity and heat can be sold for 11 JPY/kWh and 5.5 JPY/kWh, respectively. The proposed system also contributes to a reduction in the fee for the incineration of the waste. The unit price for the incineration is assumed to be 11000 JPY/t based on Sakai city. For all cases, the annual cost is much
higher than the annual revenue as shown in Fig. 6, and the cost of operation and maintenance of the anaerobic digestion plant (CP) accounts for more than 50 % of the total cost. Revenue comes primarily from the incineration of waste and the supply of heat. These results show that not all cases are economically feasible. This is because the costs of operation of the proposed system exceed the revenue from the plant. Therefore, it is important to improve methane productivity in anaerobic digestion plants by considering variables such as biomass characteristics and the method of anaerobic digestion. Also, operation and maintenance cost should be reduced and government backup such as subsidy is important.

5.3 Life cycle assessment (LCA)

The LCA calculation relating to anaerobic digestion plants consists of three main parts: material production and construction of initial facilities (MCE), operation (OE), and scrapping (SE). Total CO₂ emissions, TC, during the life cycle of the plant are calculated as follows:

\[ TC = MCE + OE \cdot LC + SE \]  

where LC is the duration of operation (20 years). Total CO₂ emissions generated during the construction of the plant are calculated by using the CO₂ emission factor of SEID (Embodied Energy and Emission Intensity Data for Japan Using Input-Output Tables) ⁷). The proposed system contributes to the reduction in CO₂ emissions from the incineration of waste and the production of electricity, heat, and chemical fertilizer. The electricity and heavy oil required for incineration are assumed to be 100 kWh/t and 0.34 L/t ⁸), respectively. More calculation details are described in Kuroda et al.⁹).

Estimated accumulated CO₂ emissions and reductions during 20 years are presented in Fig. 7. Reductions are much higher than emission, indicating that all cases are environmentally feasible. We, however, cannot ignore CO₂ emissions by the plant construction. The ratio of reductions to emissions is 3.4 for Case 1, 2.4 for case 2, and 2.7 for case 3, respectively. Fig. 8 shows the composition of CO₂ emissions. Plant construction emits most CO₂ indicating that compact design of the plant is very important. Fig. 9 shows the composition of CO₂ reductions. Incineration

![Table 5 Cost assumptions for operation and maintenance of the plant](image)

![Fig. 6 Annual cost and revenue for each case](image)

![Fig. 7 Comparison of CO₂ emission and reduction](image)

![Fig. 8 Composition of CO₂ emission](image)
of waste biomass contributed a great deal to the total reductions. Case 1 has more reductions in electricity and heat than the others because main biomass in Case 1 is tamarind, which is higher methane productivity than vegetables. These results indicate that selection of biomass considering anaerobic digestion characteristics affects the total environmental reduction.

6. Conclusions

We proposed marine biomass utilization system and investigated available waste biomass around Osaka Bay. Through the batch-processing experiments, seaweed, fishery, and tamarind were found to have high carbon recovery rate though they need careful treatment for the practical operation because of high moisture content of seaweed and high nitrogen content of fishery and tamarind. In the feasibility study, we proposed three scenarios varying waste biomass supplier. In all cases, there is big obstacle in economically feasible operation. Among three cases, the case containing tamarind was the most feasible from the economic and environmental viewpoints. The results indicated that anaerobic digestion was promising technique from the environmental perspective because it could save the fossil fuel consumption in the incineration of the waste biomass. It is required to investigate the effects of the mixture of biomass to methane yields and to conduct continuous digestion experiments to develop efficient operation considering the digestion characteristics of waste biomass.

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