An Integrated Feasibility Study of an Anaerobic Digestion Plant Using Marine Biomass and Food Waste

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In this study, we propose a marine biomass utilization system and describe an anaerobic digestion process using marine biomass and food waste. Four scenarios are presented, based on varying the amount and the main type of biomass for the anaerobic digestion plant. We conduct feasibility studies of the anaerobic digestion system from economic and environmental viewpoints. Material and energy balances are estimated in the first part of the paper, and finally we present the results of the economic and environmental analysis.

INTRODUCTION

Currently, the Japanese industry depends on foreign countries for most of its energy supply. To address this and to respond to increasing global environmental concerns, intensive efforts in leading renewable energy development have been made under government research and development (R&D) programs, the Sunshine Project, and more recently, the New Sunshine Project. Despite these efforts, the amount of renewable energy that has been practically used remains limited (Watanabe, 1995). The focus on renewable energy has increased even more since a devastating earthquake struck the Tohoku area in 2011. Among the renewable energy technologies, the Japanese government has promoted biomass utilization through the Biomass Nippon Strategy, Japan’s fundamental policy for biomass utilization. Biomass utilization is considered to be carbon neutral, replacing energy and products derived from fossil fuels with more environmentally friendly alternatives. However, the Japanese biomass resource is limited and the scale of production is small (Matsumura and Yokoyama, 2005). To date, biomass utilization in Japan has primarily been based on biomass produced on land. However, the use of marine biomass is also a good option because Japan is surrounded by sea. Marine biomass production could, in fact, be greater than land-based biomass because vast areas are available for growth and growth rates are not limited by the availability of water, potentially resulting in high levels of productivity (Gunaseelan, 1997).

Nutrient levels in enclosed seas near large industrial cities are very high because the pollution load exceeds the natural purification capacity. In these polluted waters, Ulva sp., green algae commonly known as sea lettuce, propagate rapidly and pile up in the shallows. This phenomenon is known as the green tide and has been reported in Japanese enclosed seas and in eutrophic shallow waters worldwide (Morand and Briand, 1996; Liu et al., 2009). These seaweeds are either burned or buried in the ground after collection as waste, and to date they have not been regarded as a potential energy resource.

Seaweeds reduce nutrient levels in seas and waterways because they absorb carbon and nutrients through photosynthesis. They can therefore play an important role in protecting the environment and can serve as an energy resource if the technology, which converts seaweed to energy, is practically available. One of the techniques used to convert seaweed into usable energy is anaerobic digestion. Anaerobic digestion is a biological conversion process, in which organic matter is converted to biogas consisting mainly of methane and carbon dioxide. Seaweeds can serve as an excellent feedstock for the production of methane because they are an abundant and easily biodegradable renewable resource (Chynoweth, 2002). The methane produced could then be used for heat or electricity generation, replacing fossil fuels and reducing carbon dioxide (CO₂) emissions.

From 1980 to 1983, the Japan Ocean Industries Association (JOIA) conducted a feasibility study for an energy production system incorporating seaweed cultivation and anaerobic digestion (JOIA, 1984). The results suggested that the generation of high-value by-products is necessary for a feasible operation. Kelly and Dworjanyn (2008) reviewed the anaerobic digestion of seaweed biomass carried out in Morocco, France, and Japan, and concluded that it is a viable option for the production of biogas under practical conditions. However, there are few reports on commercially operating systems. One of the reasons for the limited number of commercial operations is the low efficiency of seaweed in anaerobic digestion, and another reason is that the seaweed yield supplied from green tide and seaweed cultivation varies seasonally. In this study, we propose an anaerobic digestion system that uses both marine biomass, including seaweed, and food waste produced on land. We include food waste because it can be consistently obtained all year round, and its anaerobic digestion is more efficient than the anaerobic digestion of seaweed. We describe four scenarios for the plant and present material and energy balances. We also conduct an economic analysis and environmental assessment (life cycle assessment) to investigate the most feasible design and operation of the system.

MARINE BIOMASS UTILIZATION SYSTEM

Concept of Carbon, Nitrogen, and Phosphorus (CNP) Recycling

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
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Fig. 1 Concept of a marine biomass utilization system

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 utilization system based on CNP recycling using marine biomass is illustrated in Fig. 1 (Kuroda et al., 2011). Marine biomass produced by the green tide species is harvested before accumulation and decomposition. Seaweeds 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 (Kuroda et al., 2012). In this study, we do not consider seaweeds from green tide. A seaweed cultivation system, which promotes seaweed yield, is also a component of the input into our proposed anaerobic digestion system, along with food waste (see Fig. 2).

System Description

The anaerobic digestion system analyzed in this paper is schematically presented in Fig. 2. Marine biomass, including seaweed and fishery waste, and food wastes are pretreated to produce a slurry. Biogas, which is a mixture of methane and carbon dioxide, is produced in the anaerobic digestion process. 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.

Sakai, the second largest city (150 km²) in Osaka Prefecture, is located northeast of Osaka Bay, as shown in Fig. 3. The population of Sakai is 0.84 million, and the area available for farming is 15 km², 10% of the whole area. Sakaihama, in the northeastern part of Sakai, is the area selected for a marine biomass utilization system. Eutrophic water from the Yamato River flows into Kitahakuchi, an enclosed area, and its nutrient concentration remains very high. Therefore, Kitahakuchi is a feasible site for seaweed cultivation. Site A in Fig. 3 is a candidate site for the anaerobic digestion plant. This location is close to both the seaweed cultivation site and the commercial facility. The liquid fertilizer produced as a by-product can be used in the nearby Sakai 7-3 area, where the local government is establishing a large-scale plantation.

Suppliers of food and fishery waste chosen for the study include a vegetable-processing factory, five supermarkets, a supermarket food factory, a whole fish market, a seaside restaurant, and a fishing port. All sites except the fishing port are located in Sakai. The fishing port is located in Izumisano near Kansai International Airport (see Fig. 3). The suppliers selected for the study were interviewed, and they provided details of the type of biomass, the annual weight, and the collection times (see Table 1). There are four types of biomass: seaweed, vegetables (mainly lettuce or cabbage), meat, and fishery waste. The supermarkets, supermarket food factory, processing factory, and whole fish market can supply waste daily, while the seaside restaurant is open only on weekends and therefore can supply waste once a week. The Izumisano port can provide fishery waste once a week. Cultivated seaweed can be
Table 1 Biomass waste supplier, type of biomass, annual weight, and collection times

<table>
<thead>
<tr>
<th>Biomass supplier</th>
<th>Biomass</th>
<th>Weight [t y⁻¹]</th>
<th>Collection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vegetable-processing</td>
<td>Vegetable</td>
<td>1,800</td>
<td>Daily</td>
</tr>
<tr>
<td>factory (5 locations)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Supermarket (5 locations)</td>
<td>Vegetable</td>
<td>1,121</td>
<td>Daily</td>
</tr>
<tr>
<td>Fishery</td>
<td>Meat</td>
<td>319</td>
<td>Daily</td>
</tr>
<tr>
<td>Whole fish market</td>
<td>Fishery</td>
<td>40</td>
<td>Daily</td>
</tr>
<tr>
<td>Seaside restaurant</td>
<td>Fishery</td>
<td>1</td>
<td>Once a week</td>
</tr>
<tr>
<td>Fishing port</td>
<td>Fishery</td>
<td>25</td>
<td>Once a week</td>
</tr>
<tr>
<td>Seaweed cultivation</td>
<td>Seaweed</td>
<td>200</td>
<td></td>
</tr>
</tbody>
</table>

Table 2 Seasonal change of harvest in seaweed cultivation system

<table>
<thead>
<tr>
<th></th>
<th>Spring</th>
<th>Summer</th>
<th>Fall</th>
<th>Winter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harvest area per day [m² d⁻¹]</td>
<td>1,820</td>
<td>2,740</td>
<td>1,820</td>
<td>0</td>
</tr>
<tr>
<td>Harvest yields per day [t d⁻¹]</td>
<td>0.57</td>
<td>1.25</td>
<td>0.57</td>
<td>0</td>
</tr>
<tr>
<td>Harvest term [d]</td>
<td>90</td>
<td>80</td>
<td>90</td>
<td>0</td>
</tr>
<tr>
<td>Total yields [t]</td>
<td>50</td>
<td>100</td>
<td>50</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 3 Collection route and collection distances to the plant (one way) for each case

<table>
<thead>
<tr>
<th>Cases</th>
<th>Routes</th>
<th>Distance [km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1) Supermarkets</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>2) Seaside restaurant, Fish whole market</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>3) Fishing port</td>
<td>25</td>
</tr>
<tr>
<td>2</td>
<td>1) Supermarket food factory</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>2) Seaside restaurant, Fish whole market</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>3) Fishing port</td>
<td>25</td>
</tr>
<tr>
<td>3</td>
<td>1) Supermarkets</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>2) Seaside restaurant, Fish whole market</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>3) Fishing port</td>
<td>25</td>
</tr>
<tr>
<td>4</td>
<td>1) Vegetable processing factory</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>2) Supermarket food factory</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>3) Seaside restaurant, Fish whole market</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>4) Fishing port</td>
<td>25</td>
</tr>
</tbody>
</table>

Figure 4 Waste suppliers and annual waste

Figure 5 Biomass composition of annual waste and seaweed ratio

Case Study Scenario

We investigate four scenarios by varying the suppliers providing the food waste while maintaining a constant input from seaweed cultivation. Figure 4 shows the suppliers and annual waste for each scenario. The main suppliers are the supermarkets (five locations) and seaweed cultivation for Case 1, the supermarket food factory for Case 2, the vegetable-processing factory for Case 3, and the vegetable-processing factory and supermarket food factory for Case 4. The annual amount of waste supplied is 460 t for Case 1, 2,070 t for Case 2, 2,260 t for Case 3, and 3,870 t for Case 4. Table 3 summarizes the collection route and collection distance to the plant (one way). Figure 5 shows the annual waste classified into the four types of biomass, as well as the seaweed ratio. Cases 2–4 have a lower seaweed ratio compared with Case 1 because most of the biomass in Cases 2–4 is made up of vegetable waste from the vegetable-processing factory, supermarkets, and supermarket food factory. Cases 2 and 4 include more meat than the other cases, and also contain more fishery waste supplied by the supermarket food factory.

Anaerobic Digestion

Anaerobic digestion is a biological conversion process in which organic matter is converted to biogas consisting mainly of methane and carbon dioxide. Biomass is anaerobically digested with dilution water in a digestion tank at 35°C. The amount of dilution water required is calculated so the total solids (TS) are maintained at 8% of the volume in the digestion tank. We determine the volume of the digestion tank related to the time of digestion, which is 20 days. The anaerobic digestion plant requires heat to keep the digestion tank at a constant temperature and heat for biomass input. Also, electricity is needed for the operation of the plant. The heat required for the digestion tank is calculated below:

\[ H_i = k \cdot A \cdot \Delta T \]
waste, which are higher in TS than the other types of biomass.

where the value for meat was obtained from the literature (Lay et al., 1997). Seaweed and vegetable matter contain a lot of water; therefore, the production rate of biogas and methane from these materials is much lower than that from meat and fishery waste. The performance of anaerobic digestion mainly depends on the type of biomass (Kim and Oh, 2011); therefore, it is very important to understand the anaerobic digestion characteristics of the targeted biomass for efficient operation. The biogas produced is purified to methane gas and converted to electricity and heat by using a cogeneration system. The conversion efficiency of electricity and heat are 0.25 and 0.55, respectively.

### MATERIAL AND ENERGY

Table 5 shows the material balance in the plant for each scenario at the daily average. The ratio of dilution water to daily waste is 0.52 for Case 1, 0.96 for Case 2, 0.13 for Case 3, and 0.52 for Case 4. This indicates that Case 2 requires a large volume of water because the biomass in Case 2 contains more meat and fishery waste, which are higher in TS than the other types of biomass. Methane production per mass of daily waste is highest for Case 2 (47 Nm³ t⁻¹) and lowest for Case 3 (23 Nm³ t⁻¹) and depends on methane productivity relative to the biomass composition. As shown in Table 4, meat and fishery waste have higher methane productivity than seaweed and vegetable waste.

### ECONOMIC FEASIBILITY

#### Calculation Assumptions

We assume that the plant construction cost can be described by an approximated curve, based on five existing plants (JARUS,
2012) that contain municipal waste, agricultural food waste, and fishery waste and whose daily processed biomass is up to 25 t:

\[ y = 348.56x^{-0.759} \]  

(4)

where \( y \) is the construction cost per daily biomass weight (10\(^6\) JPY t\(^{-1}\)), and \( x \) is the maximum daily biomass weight in a year (t d\(^{-1}\)). The maximum daily biomass weight applied to Eq. 4 includes dilution water and is the biomass input in summer due to the most harvested seaweeds in summer. The weight is 3.9 for Case 1, 14 for Case 2, 9.0 for Case 3, and 19 for Case 4. Equation 4 does not consider total solids in the digestion tank and the hydraulic retention time (HRT); therefore, the estimation could lead to an underestimation of the construction cost. 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:

\[ OC = CS + CF + CP \]  

(5)

where \( CS \) is the labor cost of harvesting seaweed. The labor cost is calculated based on the number of employees over a year, labor cost per hour, and working hours per day. \( CF \) 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 7. For the labor cost of seaweed cultivation, refer to the JOBS Research Center (2012). For the labor cost of transportation and the plant, refer to the Japan Statistical Year Book 2012 (Statistics Bureau, 2012).

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\(^{-1}\) and 5.5 JPY kWh\(^{-1}\), respectively (Kawanishi et al., 2007). 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 11,000 JPY t\(^{-1}\) (Sakai City, 2012).

**Calculation Results**

The construction cost (10\(^6\) JPY) is 485 for Case 1, 658 for Case 2, 592 for Case 3, and 709 for Case 4. The construction cost per mass of daily waste (10\(^6\) JPY (t d\(^{-1}\))\(^{-1}\)) decreases with increasing weights of daily waste (123 for Case 1, 47 for Case 2, 66 for Case 3, and 37 for Case 4) because of the scale merit. 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. The ratio of revenue to cost is 0.040 for Case 1, 0.23 for Case 2, 0.25 for Case 3, and 0.40 for Case 4. 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.

**LIFE CYCLE ASSESSMENT (LCA)**

It is important that choices relating to the production system and scale are made in a way that minimizes the total environmental load. Life Cycle Assessment (LCA) is a powerful method used to analyze options and to assist with appropriate choices. In LCA, the total environmental load of a product is studied throughout its life cycle from “cradle to grave” (Bernesson et al., 2006).

**Calculation Assumptions**

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 \( CO_2 \) emissions, \( TC \), during the life cycle of the plant are calculated as follows:

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

(6)

where \( LC \) is the duration of operation (20 years). Total \( CO_2 \) emissions generated during the construction of the plant are calculated by using the \( CO_2 \) emission factor of 3EID (Embodied Energy and Emission Intensity Data for Japan Using Input-Output Tables) proposed by NIES (2000). The value for \( CO_2 \) emissions from material production and construction is assumed to be as follows:

\[ MCE = \alpha_{CC} \cdot CC \]  

(7)
where $MCE$ is the estimated CO$_2$ emissions from the material production and construction of the anaerobic digestion plant, $\alpha_{CC}$ is the CO$_2$ emission factor of nonresidential construction except for wooden structures (code #411202, category 283, and (I-A)$^{-1}$ meaning that includes import products), and $CC$ is the construction cost.

With regard to the operation of the plant, we do not include the CO$_2$ emissions generated by anaerobic digestion based on the concept of carbon neutrality. Therefore, the carbon emissions generated during the operation come from the harvesting of seaweed, the land transport of waste, and the supplemental electricity for the plant. In a seaweed cultivation system, we consider the CO$_2$ emissions produced by an employee harvesting seaweed, $HC$, which are assumed to be equal to the amount of CO$_2$ emitted from human breath in a day:

$$HC = \alpha_{HC} \cdot n_w$$  \hspace{1cm} (8)

where $n_w$ is the number of employees over a year, as shown in Table 5. The CO$_2$ emissions from transportation, $TR$, are calculated as follows:

$$TR = \alpha_{EL} \cdot \frac{DIS}{FEF}$$  \hspace{1cm} (9)

where $\alpha_{EL}$, $DIS$, and $FEF$ are the CO$_2$ emission factors for light oil, the transport distance between collection sites and the plant, and the fuel efficiency of light oil, respectively. $FEF$ is assumed to be 3.09 km L$^{-1}$ for a 10-t truck. The CO$_2$ emissions related to the supplemental electricity, $CEL$, are calculated by using the CO$_2$ emission factor for electricity:

$$CEL = \alpha_{EL} \cdot EL$$  \hspace{1cm} (10)

where $\alpha_{EL}$ is the CO$_2$ emission factor for electricity, and $EL$ is the electricity consumed (kWh). Therefore, CO$_2$ during the operation, $OE$, is represented as follows:

$$OE = HC + TR + CEL$$  \hspace{1cm} (11)

The CO$_2$ emissions generated by scrapping, $SE$, are assumed to be 4.8% of the emissions generated during construction and are expressed as follows:

$$SE = 0.048 \cdot \alpha_{CC}$$  \hspace{1cm} (12)

The proposed system contributes to the reduction in CO$_2$ 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$^{-1}$ and 0.34 L t$^{-1}$, respectively (Hirai et al., 2001). Emissions from the production of electricity and heat are obtained by using the CO$_2$ emission factors summarized in Table 8. The reduction in emissions by using liquid fertilizer is calculated by using the factor for CO$_2$ emissions through the life cycle, including the production and transportation of chemical fertilizer (Kobayashi and Sago, 2001).

**Calculation Results**

Estimated accumulated CO$_2$ emissions for 20 years are presented in Fig. 7. The CO$_2$ emissions for plant construction increase with an increase in the daily weight of biomass to be processed. Case 2 has the lowest CO$_2$ emissions for waste collection on land because it does not include waste from the supermarkets (five locations) and vegetable-processing factory, which require the highest amounts of

<table>
<thead>
<tr>
<th>Term</th>
<th>Factor</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction of the plant</td>
<td>$\alpha_{CC}$</td>
<td>3.24</td>
</tr>
<tr>
<td>Employee</td>
<td>$\alpha_{HC}$</td>
<td>0.001</td>
</tr>
<tr>
<td>Light oil</td>
<td>$\alpha_{LO}$</td>
<td>2.58</td>
</tr>
<tr>
<td>Electricity</td>
<td>$\alpha_{EL}$</td>
<td>0.475</td>
</tr>
<tr>
<td>City gas for heat</td>
<td>–</td>
<td>0.0509</td>
</tr>
<tr>
<td>Heavy oil for incineration</td>
<td>–</td>
<td>2.71</td>
</tr>
<tr>
<td>Chemical fertilizer</td>
<td>–</td>
<td>1.6</td>
</tr>
</tbody>
</table>

Table 8  CO$_2$ emission factors

**Fig. 7** Accumulated CO$_2$ emissions and the contributing factors during 20 years of operation

light oil for transportation. Case 4 has the lowest emission rate per daily averaged waste at 239 t CO$_2$ (t d$^{-1}$)$^{-1}$, while Case 1 has the highest rate at 1,820 t CO$_2$ (t d$^{-1}$)$^{-1}$. The emission rate for Case 1 is about four to eight times higher than that for the other cases.

Table 9 summarizes the reduction in CO$_2$ emissions for each case based on the yearly averaged biomass input. The proposed system contributes to reductions in CO$_2$ produced during the incineration of waste, heat, and chemical fertilizer. The calculation of CO$_2$ emissions regarding the incineration of waste does not count seaweed in seaweed cultivation, because it is newly produced in the marine biomass utilization system. The reduction in CO$_2$ emissions increases with increasing volumes of daily waste. Only Case 4 reduces emissions related to electricity generation, because it provides electricity to the commercial facility. In all cases, the largest reduction in CO$_2$ emissions is related to incineration and heat production. Figure 8 illustrates the comparison between accumulated CO$_2$ emissions and the reduction in CO$_2$ emissions during operation. The ratio of CO$_2$ emission to reduction for Case 1

<table>
<thead>
<tr>
<th>Term</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incineration</td>
<td>13</td>
<td>90</td>
<td>100</td>
<td>178</td>
</tr>
<tr>
<td>Electricity</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Heat</td>
<td>11</td>
<td>80</td>
<td>41</td>
<td>110</td>
</tr>
<tr>
<td>Chemical fertilizer</td>
<td>4</td>
<td>21</td>
<td>13</td>
<td>30</td>
</tr>
<tr>
<td>Total</td>
<td>28</td>
<td>191</td>
<td>154</td>
<td>320</td>
</tr>
</tbody>
</table>

Table 9  CO$_2$ emission reductions relating to fuel for incineration, electricity, heat, and chemical fertilizer (t y$^{-1}$)
is high at 4.2, indicating CO$_2$ emissions are beyond reduction. Conversely, Case 4 has the most significant CO$_2$ reductions with values of 0.42. The reduction rate, which is defined as the CO$_2$ reduction per daily weight of biomass, is also shown in Fig. 8. The results show that Case 2 can efficiently reduce CO$_2$ emissions; however, Case 1 emits more CO$_2$ than it reduces. This indicates that all cases, except for Case 1, are feasible from the environmental viewpoint. Among them, Case 2 is the most effective in reducing CO$_2$ emissions. The efficiency of anaerobic digestion and the composition of biomass are important considerations for maximizing the reduction in CO$_2$ emissions.

CONCLUSIONS

We propose a system to use marine biomass and food waste and conduct a feasibility study of the system focusing on anaerobic digestion as an energy conversion technique. We present four scenarios based on varying the scale of the plant and considering the suppliers of biomass in Sakai, and we investigate the feasibility from economic and environmental viewpoints. The results of the economic analysis indicate that not all cases are feasible, with high costs involved in the operation and maintenance of the plant. One advantage is that the proposed system contributes to a reduction in the cost of incineration. From an environmental viewpoint, all cases, except for Case 1, are feasible, because there is a reduced requirement for fuels for incineration and a supply of heat is made available to the commercial facility. The collection and transportation of biomass is costly, and its CO$_2$ emission cannot be ignored. Among four scenarios, Case 4 is the most feasible in both economic and environmental aspects. In contrast, among other anaerobic digestive plants, some successfully upgrade biogas to natural gas for injection into the gas grid (Poeschl et al., 2010), while others profitably use the digestive (Delzeit and Kellner, 2013). These examples suggest that the infrastructure and the technique of processing the digestate are also key factors for feasible anaerobic digestion.

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REFERENCES


Fig. 8 Accumulated CO$_2$ emissions, reductions, and reduction rate

The reduction rate, which is defined as the CO$_2$ reduction per daily weight of biomass, is also shown in Fig. 8. The results show that Case 2 can efficiently reduce CO$_2$ emissions; however, Case 1 emits more CO$_2$ than it reduces. This indicates that all cases, except for Case 1, are feasible from the environmental viewpoint. Among them, Case 2 is the most effective in reducing CO$_2$ emissions. The efficiency of anaerobic digestion and the composition of biomass are important considerations for maximizing the reduction in CO$_2$ emissions.