Economic Evaluation for Energy Recycling System by Oil-Water Separation Equipment in Food Processing Factory

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This study aimed to propose economic evaluation method for installing oil-water separation equipment into wastewater treatment system to attain energy recycling system in a food processing factory using Value Function (VF) and Separative Work Unit (SWU) of separation engineering. VF for calculating SWU was determined by the field investigation at the food processing factory, Naoetsu-Yushi Co. Ltd. The results showed the required ability of the oil-water separation equipment to obtain a profit as at least 10% in this simulation for the food processing factory. More, the recovery period (payback time) of the initial cost for installing the oil-water separation equipment and the wastewater treatment facility at 0% of discount rate was calculated as 162.6 months, which was shorter than the lifetime of them and it shows the economic feasibility of installing the oil-water separation equipment. The proposed method could achieve the comparison of different equipment or different conditions for total performance improvement, and help the selection of the alternative equipment or the implement of the surrounding condition.

Key Words
Economic evaluation, Oil-water separation, Separation engineering, Separative Work Unit, Value Function, Wastewater treatment

1. Introduction

From the viewpoint of reduction of environmental load and efficient use of biomass, food waste recycling attracts more attention. Hyde et al. 1) reported that the East Anglian Waste Minimisation project in the food and drink industry demonstrated 12% of raw materials reduction to achieve significant contribution to company profitability, and Khoo et al. 2) conducted environmental evaluation of the food waste recycling facilities in Singapore using life cycle assessment (LCA). In Japan, Food Waste Recycling Law was established in 2000. Tanaka et al. 3) conducted environmental and economical evaluations toward some recycling facilities for food waste using LCA and LCC (Life Cycle Cost).

The vegetable and/or animal oils in wastewater are often discharged from food processing factories and restaurants. The oil in wastewater causes degradation of drainage water quality and deterioration of performance for the wastewater treatment facility. Additionally, it increases the management cost for cleaning and maintenance of a sewer pipe and wastewater treatment facilities as social

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problem. Recently, wastewater management cost is increased and it brings serious problems to the food processing and restaurant companies due to the environmental policy of the government. Therefore, these companies pay close attention to wastewater that is contaminated by the oil.

Oil-water separation is one of the key technologies to solve the wastewater management problems. There are many technologies for separating oil and water, including centrifugation, floatation, flocculation, and/or absorption. Therefore, selection and design for appropriate oil-water separation equipment to wastewater management is an important issue. Finally, recovery of the oil from wastewater would increase not only performance level of the wastewater treatment facility without plumbing blockages, but also profit from the recovered oil in energy recycling system. That is, installing oil-water separation equipment to wastewater treatment system offers an opportunity to generate a huge profit of energy and cost from wastewater that would otherwise be wasted. In addition, improved efficiency of factory’s wastewater treatment facilities is expected to result in substantial cost reduction.

In most previous research about oil-water separation as energy recycling, the amount of recovered oil or CO₂ reduction is the center of interests. On the other hand, from the macro perspective, oil removed water as water resource has significant value. Then, the evaluation method that consider wider range of oil-water separation as system was required.

When a decision-maker of a food processing factory attempts installing oil-water separation equipment, an economic evaluation method is required for management because low cost and high performance of oil-water separation equipment shows trade-off relation, generally.

The purpose of this study is to propose an economic evaluation method for installing oil-water separation equipment into the oil containing wastewater to attain energy recycling system in a food processing factory using Value Function (VF) and Separative Work Unit (SWU) of separation engineering.

2. Materials and Methods

2.1 Flow of Oil-Water Separation

Separation equipment generates valuable resources (products) and valueless resource (wastes) in downstream from feedstock of upstream. In the concept of oil-water separation in a food processing factory (Fig. 1), oil-water separation equipment separates the recovered oil and the oil removed water in downstream using wastewater treatment system from the oil containing wastewater in upstream. Economic value of the recovered oil and the oil removed water depends on their amount and purity (concentration). Then, effective and economical separation equipment should be selected to a food processing factory.

Where, \(O_{\text{out}}\) [kg/day], \(W_{\text{out}}\) [kg/day] and \(W_{\text{in}}\) [kg/day] are, respectively, the amount of the recovered oil per day, of the oil removed water per day, and of the oil containing wastewater per day. \(X_{\text{out}}\) [-], \(X_{\text{in}}\) [-] and \(X_{\text{win}}\) [-] are defined as the oil mixing ratio in the recovered oil, the oil removed water and the oil containing wastewater, respectively. Higher mixing ratio of oil and other contaminants in wastewater brings the increase in the workload required for water purification. The relation between the six variables is expressed by the following equation.

\[
O_{\text{out}} \cdot X_{\text{out}} + W_{\text{out}} \cdot X_{\text{out}} = W_{\text{in}} \cdot X_{\text{win}} \quad (1)
\]

2.2 Value Function and Separative Work Unit

SWU is the scale of treatment ability of separation process, widely used in the field of nuclear power engineering and so on. VF is the function used to calculate SWU and convert concentration \(X\) to the economic value. Generally, \(V(X)\) of VF is decided based on entropy change in separation engineering, as below.

\[
V(X) = (2X - 1) \ln \frac{X}{1 - X} \quad (2)
\]

Equation (2) is used only for the case that separation produces a product and a waste from feedstock in separation engineering. However, oil-water separation of this research produces both oil and water as valuable resources without waste. Thus, eq. (2) is not suitable for this research. More, eq. (2) expresses the value of separation on the assumption of physically ideal condition based on theory.
of informational entropy. However, oil-water separation is not categorized to using eq. (2) because it is not on ideal condition and applicative evaluation should count the additional values of oil as combustion energy and water as decreasing of wastewater treatment cost.

Therefore, VF of oil-water separation in a food processing factory should be defined for each product with single unit. Then, \( f(X_{\text{Oout}}) \) [JPY/kg], \( g(X_{\text{Wout}}) \) [JPY/kg] and \( h(X_{\text{Win}}) \) [JPY/kg] are assumed as VF of the recovered oil, the oil removed water and the oil containing wastewater respectively, which was defined by the economic value of oil and water considering with mixing ratio of them.

\[
\delta U_s = O_{\text{out}} \cdot f(X_{\text{Oout}}) + W_{\text{out}} \cdot g(X_{\text{Wout}}) - W_{\text{in}} \cdot h(X_{\text{Win}}) \quad (3)
\]

2.3 Material and energy flow

The food processing factory, Naoetsu-Yushi Co. Ltd., was taken as the experimental site to apply the calculation of VF and SWU. The factory produced boiled chicken from culled chicken, and high temperature steam was used for boiling, and abundance of chicken oil flown out with the wastewater after boiling process. In an attempt to solve these problems of wastewater treatment by this abundance of chicken oil, the oil–water separation equipment was installed into the wastewater treatment system of the factory.

The oil–water separation equipment operated on the basis of the specific gravities of oil and water, and on the speed control of wastewater flowing inside the equipment without chemical and biological treatments. As a result, there were no quality changes in the water and no seasonal changes in the treatment volume. The energy and material flow of the factory is shown in Fig. 2. The recovered oil was used as fuel for the steam boiler. The oil removed water was purified by the wastewater treatment facility, and the purified water was used for melting snow inside the food factory in winter season. In other seasons, part of the purified water was used for water of plants and most of it was released into the river. As other possible way, hot-air heating within the factory or indirect heat source by purified water is under consideration.

Most of contaminant in wastewater from chicken boiling process except oil was suspended solids (SS) that consists mainly of protein and starch. From the field investigation, the concentration of SS (1,100 mg/L) was revealed to be small compared to the concentration of oil (19,000 mg/L) in the wastewater. More, our investigation showed that SS was recovered easily from wastewater after applying oil-water separation equipment. Then, on the assumption that contaminants except oil could be removed easily, the wastewater was treated as containing only oil and water, and the separation of these resources was the focus of the calculation. The pressure and temperature of the wastewater were assumed to be same before and after the separation.

![Fig. 2. Material and energy flow of the food processing factory, Naoetsu-Yushi Co. Ltd.](image-url)
2.4 Value Function for the food processing factory

The VF was determined by the field investigation at the food processing factory. As the recovered oil was used as fuel to the steam boiler, the VF of \( f(X_{\text{out}}) \) was determined by the heating value and can be expressed as follows.

\[
f(X_{\text{out}}) = V_{\text{heat}} \cdot (X_{\text{out}} \cdot H_{\text{oil}} - (1 - X_{\text{out}}) H_{\text{wat}}) \tag{4}
\]

Where \( V_{\text{heat}} \) [JPY/J] is the conversion factor from heating value to economic value, \( H_{\text{oil}} [/kg] \) and \( H_{\text{wat}} [/kg] \) are the heating value of oil and water, respectively.

When \( X_{\text{out}} \) was not 100% that meant the recovered oil contained water, total evaporating energy of water in the recovered oil should be considered for estimating the heating value of the oil. As a result, the VF of \( f(X_{\text{out}}) \) increased linearly from the negative heating value at 0% of \( X_{\text{out}} \).

The initial cost and the running cost of the wastewater treatment facility are traditionally determined by the permissible amount of wastewater per day because the wastewater treatment facility could treat only oil-less or low oil containing wastewater, not much oil containing wastewater from a food processing factory. Then, the standard for these costs of the wastewater treatment facility that should treat oil containing wastewater is not clear. Therefore, \( P_i \), the initial cost of the wastewater treatment facility that should treat oil containing wastewater, and \( P_r \), the running cost of the wastewater treatment facility that should treat oil containing wastewater were assumed to be determined by its scale for the maximum permissible concentration of the n-hexane extracts \( N \) [mg/L] \( ^{18} - ^{24} \), and expressed as follows.

\[
P_i = p_i \cdot \frac{a}{A \cdot N} \cdot A = p_i \cdot \frac{a}{N} \tag{5}
\]

\[
P_r = p_r \cdot \frac{a}{A \cdot N} \cdot A = p_r \cdot \frac{a}{N} \tag{6}
\]

Where \( N \) [mg/L] is the maximum permissible concentration of the n-hexane extracts, \( a \) [kg] and \( A \) [L] are the amount of the oil in the oil containing wastewater per day and the amount of the oil containing wastewater per day, respectively. \( p_i \) [JPY/L] and \( p_r \) [JPY/L] are the standard initial and running costs of the wastewater treatment facility per the total amount of wastewater that is treated over a lifetime of wastewater treatment facility, respectively.

Recovering oil from the oil containing wastewater contributes to the cost reduction of the wastewater treatment facility. \( p_e \) [-] is the specific gravity of the wastewater that changes with the \( X_{\text{win}} \) or \( X_{\text{wout}} \). \( P_{\text{sep}} \) [JPY/L] is the initial cost of the oil-water separation equipment per the amount of treated wastewater over a lifetime of it. \( E_{\text{sep}} \) [kWh/L] is the input energy (electricity) of the oil-water separation equipment per the total amount of treated wastewater over a lifetime of it and \( \eta \) [JPY/kWh] is the conversion factor between cost and energy.

Considering the initial and running costs of the wastewater treatment facility, \( h(X_{\text{win}}) \) [JPY/kg] as the VF for the wastewater treatment facility without the oil-water separation equipment, and \( g(X_{\text{wout}}) \) [JPY/kg] as the VF for the wastewater treatment facility with the oil-water separation equipment were determined as below. The VFs of \( h(X_{\text{win}}) \) and \( g(X_{\text{wout}}) \) decrease almost linearly with an increase of \( X_{\text{win}} \) and \( X_{\text{wout}} \).

\[
h(X_{\text{win}}) = \frac{P_i + P_e}{\rho_w \cdot N} = \left( \frac{P_i + P_e}{\rho_w} \right) \cdot X_{\text{win}} \tag{7}
\]

\[
g(X_{\text{wout}}) = h(X_{\text{wout}}) - \frac{P_{\text{sep}}}{\rho_w} \cdot \frac{E_{\text{sep}} \cdot \eta}{\rho_e} \tag{8}
\]

3. Results and Discussions

3.1 SWU for general factory and objective factory

The specific data to decide VFs in the food processing factory, Naoetsu-Yushi Co. Ltd., is listed in Table 1 and the determined VFs based on Table 1 is shown in Figs. 3-5 expressed by the following equations, \( f'(X_{\text{out}}) \), \( h'(X_{\text{win}}) \) and \( g'(X_{\text{wout}}) \). The difference between \( h'(X_{\text{win}}) \) and \( g'(X_{\text{wout}}) \) were relatively small, because the initial cost and input energy of the oil-water separation equipment was small compared with the wastewater treatment facility.

\[
f'(X_{\text{out}}) = 92.6 \cdot X_{\text{out}} - 5.3 \tag{9}
\]

\[
h'(X_{\text{win}}) = -124.0 \cdot X_{\text{win}} \tag{10}
\]

| Variable                | Value      | Unit       |
|-------------------------|------------|------------|
| Heating value of fuel oil A | 391[10] MJ/L |
| Price of fuel oil A     | 907[10] JPY |
| \( V_{\text{heat}} \)  | 0.000000232 JPY/J |
| Heating value of chicken oil | 9000[18] kcal/kg |
| \( H_{\text{wat}} \)   | 37,656,000 J/kg |
| \( H_{\text{win}} \)   | 2,270,000 J/kg |
| \( a \)                 | 183[10] kg |
| \( A \)                 | 40,000[10] L |
| \( N \)                 | 0.000000[18] kg/L |
| \( E_{\text{sep}} \)   | 0.00000225 [kWh/L] |
| \( \eta \)              | 15.53[21] JPY/kWh |
| Specific gravity of animal oil | 0.915[15] |
| Specific gravity of water | 1[21] |
| Wastewater treatment facility | Lifetime | 15 * year |
| Initial cost            | 60,000,000 JPY |
| Running cost            | 307,205 JPY/month |
| Oil-water separation equipment | Lifetime | 15 * year |
| Initial cost            | 130,000,000 JPY |

Marked *: Obtained in field investigation.
Horizontal line of Fig. 6 shows the purity of the recovered oil, which is equal to the separation ability of the oil-water separation equipment. The calculated result was approximated by the following equation.

\[
\delta U'_{s} = 39600 W_{\text{out}} - 3300 \quad (13)
\]

If \( X_{\text{out}} \) was 0, the oil-water separation equipment was not required for the wastewater treatment system. Positive value of SWU meant that profit by the recovered oil and the oil removed water was larger than cost for the oil-water separation equipment and the wastewater treatment facility. Therefore, over 0 of SWU by changing the value of \( X_{\text{out}} \) showed a profit by using the oil-water separation equipment. In this simulation, at least 10% of the separation ability was required to attain positive value of SWU (Fig. 6).
3.2 Recovery period (payback time)

The initial cost, the running cost, and the required periods for recovery of the initial cost of the oil-water separation equipment and the wastewater treatment facility are listed in Table 2. The SWU calculation for the food processing factory gave a result of 722,282 JPY/month (20 days operation per month) using 0.0046 of $X_{\text{Win}}$ and 99.5% of the separation ability of the oil-water separation equipment. Profit of SWU was used for the running cost and recovering the initial cost. Recovery period (payback time) for the oil-water separation equipment and the wastewater treatment facility was 162.6 months (13.5 years) at 0% of discount rate. Lifetime of the oil-water separation equipment and the wastewater treatment facility was estimated to be 15 years (Table 2). The results indicated that surplus recovered SWU had profit after recovery of the total initial cost until the lifetime (13.5 years to 15 years after installing). In this case, installing the oil-water separation equipment into the food processing factory at 0% of discount rate was revealed to be economically feasible.

On the other hand, discount rate affected the recovery period (Fig. 7). Under 2 % of discount rate, the recovery period for the oil-water separation equipment and the wastewater treatment facility was shorter than the lifetime of them that means economic feasibility (Table 3). Over 2 % of discount rate, payback could be difficult within the lifetime. However, considering some cases that effective oil-water separation equipment is installed to an existing wastewater treatment facility, the recovery period only for the oil-water separation equipment was below 2 years (Table 3), shorter enough to payback within lifetime, even at 10 % of discount rate.

3.3 Required separation ability for payback

On the other hand, in the case where the lifetime of the current oil-water separation equipment are 15 years, surplus of 405,556 JPY/month were required to recover the total initial cost, 73 million JPY of the oil-water separation equipment and the wastewater treatment facility. Added the total monthly running cost of 307,206 JPY, the required total profit are 712,762 JPY/month (35,638 JPY/day). The result shows over 98.3% of the separation ability was required in operation to recover the initial cost within a lifetime of the oil-water separation equipment and the wastewater treatment facility (Fig. 6) at 0% of discount rate.

### Table 2 Initial and running costs of the oil-water separation equipment and the wastewater treatment facility and calculation results of recovery period

|                        | Oil-water separation equipment | Wastewater treatment facility |
|------------------------|-------------------------------|-------------------------------|
| Initial cost [JPY]     | 13 million                    | 60 million                    |
| Running cost [JPY/month]| 1.35                          | 307,206                       |
| Recovery period for initial cost [month] | 18.0                        | 144.6                         |
| Total recovery period [month] | 162.6                      |
| Lifetime [month]       | 180                           |                               |

### Table 3 Recovery period of the oil-water separation equipment and the wastewater treatment facility considering discount rate

| Discount rate [%] | Oil-water separation equipment and Wastewater treatment facility | Only oil-water separation equipment |
|-------------------|---------------------------------------------------------------|-----------------------------------|
| 0                 | 13.7                                                          | 17                                |
| 1                 | 14.8                                                          | 17                                |
| 2                 | 16.2                                                          | 17                                |
| 3                 | 17.9                                                          | 17                                |
| 4                 | 20.2                                                          | 17                                |
| 5                 | 23.6                                                          | 18                                |
| 6                 | 29.4                                                          | 18                                |
| 7                 | 46.2                                                          | 18                                |

Fig. 7 Cumulative SWU considering discount rate (Solid line: total payback cost of the oil-water separation equipment and the wastewater treatment facility, dotted line: total payback cost of the oil-water separation equipment)

### Table 3 Recovery period of the oil-water separation equipment and the wastewater treatment facility considering discount rate

| Discount rate [%] | Recovery period [Year] |
|-------------------|------------------------|
| 0                 | 13.7                   |
| 1                 | 14.8                   |
| 2                 | 16.2                   |
| 3                 | 17.9                   |
| 4                 | 20.2                   |
| 5                 | 23.6                   |
| 6                 | 29.4                   |
| 7                 | 46.2                   |

3.4 Comparison of different technologies

As an example, the SWU of the current equipment (initial cost: 13 million JPY) and an alternative equipment (initial cost: 6 million JPY) are shown in Fig. 8. In this
simulation, the two were assumed as having same specs except for the initial cost and the separation ability ($X_{\text{Oout}}$). If the two have same separation ability and different initial cost, the SWU of the alternative equipment that had lower initial cost shows higher SWU than the current equipment. However, the initial cost and the separation ability of oil-water separation equipment have a trade-off relation, generally. When the expensive and high performance current equipment (initial cost 13 million JPY, $X_{\text{Oout}} 0.95$), and the cheaper and lower performance alternative equipment (initial cost 6 million JPY, $X_{\text{Oout}} 0.90$) were compared, the SWU were 34,330 JPY/day and 33,619 JPY/day, respectively. This result shows that even if the initial cost was decreased by more than half by installing the alternative equipment, the decrease by 5% in the separation ability indicated lower SWU, the reduction of total profit, which was not suitable for the alternative.

The comparison of the payback time for each equipment was shown in Fig. 9. Except 0% of discount rate, payback time of them was longer than the lifetime. Payback time of the alternative based on lower SWU and initial cost is shorter than the current equipment based on higher SWU and initial cost. More, the difference between them was increasing progressively according to increased discount rate. Therefore, when discount rate is at 0% or low, the current equipment was desirable, and when the discount rate increases, the alternative would be selected. Therefore, SWU of this method could achieve the comparison of the different technology or different conditions with trade-off relation for total performance improvement of a food factory.

4. Conclusions

1) Value Function (VF) and Separative Work Unit (SWU) were applied to the economic evaluation for the wastewater management system using the oil-water separation equipment in the food processing factory, Naoetsu-Yushi Co. Ltd.

2) Required ability of the oil-water separation equipment to obtain a profit was determined as at least 10% in this simulation for the food processing factory with 0.0046 of the oil mixing ratio in oil containing wastewater $X_{\text{Win}}$ (oil 183 kg, wastewater 40,000 L).

3) Initial cost recovery period for installing the oil-water separation equipment and the wastewater treatment facility was calculated as 162.6 months for the food processing factory at 0% of discount rate.

4) The proposed method could achieve the comparison of different equipment or different conditions with trade-off relation for total performance improvement of a food factory.

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