Economic Evaluation of Wastewater Treatment System Based on Recovery Characteristics of Oil and Suspended Solids by Filtration

Eriko ANKYU[※1†], Toshihiko OTSUKA[※1], and Ryozo NOGUCHI[※2]

Filtration experiments were conducted using artificial wastewater at 20 °C and 60 °C to explain the relationship between the separation ability of oil-water separation equipment and the recovery rate of suspended solids (SS) recovery equipment for oil concentrations. Based on the characteristics of oil and SS explained by the filtration experiments, an economic evaluation method for a wastewater treatment system was proposed for two cases: using oil-water separation equipment without SS recovery equipment (single use) and using oil-water separation equipment with SS recovery equipment (combination use) using Separative Work Unit (SWU). The separation ability of oil-water separation equipment could determine the required recovery rate of SS recovery equipment. The SWU for combination use at 20 °C and 60 °C was higher than the SWU for single use. The SWU for combination use at 60 °C was higher than that at 20 °C. At 60 °C, combination use increased the SWU by 562 JPY/day (treatment amount 3,000 L/day) compared to single use, at 45% separation ability of the oil-water separation equipment according to the results of our filtration experiments.

　水温 20℃と 60℃の模擬排水を用いて濾過実験をおこない，油の濃度に対する油水分離装置の分離性能と SS 回収装置の回収率の関係を明らかにした。濾過実験で明らかになった油と SS の濾過特性にもとづき，油水分離装置を用いて SS 回収装置を用いない単独使用（single use）と，油水分離装置と SS 回収装置を使用する併用使用（combination use）の2条件に対して，分離作業量（SWU）を用いて排水処理システムの経済性評価手法の提案を行った。油水分離装置の分離性能が決まることによって，必要な SS 回収装置の回収率が決定された。水温 20℃と 60℃における併用使用の分離作業量は，単独使用の分離作業量よりも高い値を示した。水温 60℃における併用使用の分離作業量は水温 20℃における併用使用の分離作業量よりも高い値を示した。我々が行った濾過実験実験での水温 60℃の条件において，併用使用では，単独使用に比べて油水分離性能が 45%のとき分離作業量が 562 円 / 日（処理量 3,000 L/ 日）上昇した。

1. Introduction

Wastewater from food processing factories, restaurants, and food shops includes large amounts of animal and vegetable oil. This oil causes various problems for wastewater treatment, such as decreasing the efficiency of the wastewater treatment facility, and increasing running costs of the facility [1]. Grease traps for collecting oil in wastewater are typically set in food processing factories, restaurants, and food shops in Japan. However, they are not effective for wastewater that includes a large amount of oil, and wastewater that still contains a little amount of oil overflowed downstream. Wastewater flowing into river bodies causes odor problems and water contamination. Wastewater flowing into sewage system is one of the causes of blocked drains and pipes. In some cases, consolidated oil forms oil balls that draft into the sea [2]. Moreover, running cost and time for wastewater treatment facilities increase if wastewater includes a large amount of oil. Although food processing factories, restaurants, and food shops are allowed to release only a limited concentration of oil in wastewater below the effluent standard, set by the Water Pollution Control Law in Japan, they still release wastewater including a large amount of oil.

There are many studies on using microorganisms

※1　Graduate School of Life and Environmental Sciences, University of Tsukuba
1-1-1, Tennodai, Tsukuba, Ibaraki 305-8577, Japan

※2　Faculty of Life and Environmental Sciences, University of Tsukuba
1-1-1, Tennodai, Tsukuba, Ibaraki 305-8577, Japan

†　Corresponding author: eri.an9193@gmail.com

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in wastewater treatment by introducing them into grease traps [3] ~ [6]. However, these methods produce a large amount of residue, increasing the initial and running cost of underground grease traps, and slowing the speed of the treatment process. Using oil-water separation equipment for recovering oil from wastewater before releasing it into the treatment facility that includes a grease trap increases the efficiency of the treatment facility, reduces initial and running costs, and makes it possible to reuse the recovered oil as an energy resource [7] [8]. In a previous study [9], an economic evaluation of installing oil-water separation equipment into a wastewater treatment system in a food processing factory was conducted.

Wastewater from food processing factories, restaurants, and food shops includes not only oil but also large volumes of suspended solids (SS) such as food residue, composed mainly of protein and starch. If high performance oil and SS recovery can be achieved, the total workload and running costs of wastewater treatment would be dramatically reduced. Furthermore, recovered oil and SS can serve as significant sources of additional profit if oil and SS can be collected with no chemical change. Thus, the separation ability of oil-water separation equipment and the recovery rate of SS recovery equipment affect the economics of the treatment process.

This study aims to evaluate the economics of installing oil-water separation and SS recovery equipment on a wastewater treatment system using the recovery characteristics of oil and SS by filtration and Separative Work Unit (SWU).

First, filtration experiments representing SS recovery equipment were conducted using artificial wastewater to identify the relationship between the separation ability of oil-water separation and the recovery rate of SS recovery equipment for oil concentration. Since high performance SS recovery can be achieved empirically by reducing oil concentration in wastewater through filtration, artificial wastewater with changing concentrations of oil and SS was used in the filtration experiments to calculate the recovery rate of oil and SS. Second, an economic evaluation method was proposed to evaluate the installation of oil-water separation and SS recovery equipment on a wastewater treatment system based on a previous study [9].

2. Materials and Methods

2.1 Filtration experiments for recovery characteristics of oil and SS using different oil concentrations of artificial wastewater

The concept of oil-water separation and SS recovery in this study is illustrated in **Fig. 1**. Oil-water separation equipment recovered oil from oil- and SS-containing wastewater. Next, SS recovery equipment recovered SS from oil-removed water. Oil- and SS-removed water was then treated at the wastewater treatment facility. The study site of evaluation was a fictional family restaurant or a food shop (the model restaurant) that discharges wastewater including large amounts of oil and SS.

Oil-water separation equipment assumed in this study was operated based on the specific gravity of oil and water and on the wastewater flow rate inside the equipment, without chemical or biological treatment. As a result, there were no water quality changes. Filtration equipment was selected to act as a SS recovery equipment after oil-water separation and before wastewater treatment, because recovering SS upstream of a wastewater treatment facility decreases the cost and size of the facility and increases the possibility of using recovered SS as a recycled resource. A pouched grid mesh was used as a SS recovery equipment.

It is not proper to use wastewater from actual food processing factories, restaurants, and food shops in the filtration experiments because there is a wide range of elements including the components in actual wastewater, and temperature and flow velocity of actual wastewater. In this study, filtration results of artificial wastewater
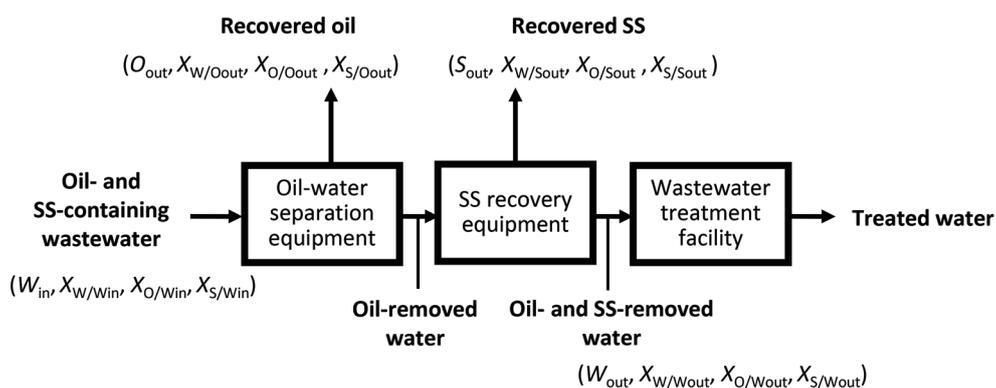

Fig. 1 Concept of oil-water separation and SS recovery in a wastewater treatment system

containing vegetable oil and flour (as SS) were used for the economic evaluation. To comparison, actual wastewater from the cafeteria of the University of Tsukuba in December 2016 was also used.

Filtration experiments using artificial wastewater with varying concentrations of oil and SS as oil-removed water were conducted to identify the relationship between the separation ability of oil-water separation equipment and the recovery rate of SS recovery equipment. The mesh had 0.44-mm openings and a thread diameter of 0.20 mm, similar to the ones installed on food preparation facilities. One sheet of mesh cut into roughly 40-mm squares was used in each filtration trial. The filtration unit including the mesh sheet is shown in **Fig. 2**. A filtration tray (inner diameter 54.0 mm, hole diameter 21.5 mm, height 20.0 mm) was placed on the mesh sheet. The effective filtration area was 3.64×10^2 mm^2. The inlet velocity of artificial wastewater was 0.017–0.020 L/s, which ensured constant velocity and inlet time.

Artificial wastewater was composed of water, sunflower oil as oil, and flour as SS. Flour was selected because it has inconsistent particle size (5–100 μm [10]) and is mainly composed of protein and starch.

Experimental conditions consisted of 42 combinations of six oil concentrations (0.5, 1.0, 1.5, 2.0, 2.5, and 3.0 g/L) and seven SS concentrations (0.5, 1.0, 1.5, 2.0, 2.5, 3.0, and 3.5 g/L). Maximum values were determined based on the data collected during a field investigation.

Variation in mesh weight before and after drying over one day was measured. The recovery rate of oil and SS by filtration was expressed as the variation in mesh weight divided by the sum of sunflower oil and flour in artificial wastewater (eq. (1)), where R is the recovery rate of oil and SS by filtration, ΔW_m is the variation in mesh weight (W_m) before and after filtration and drying, and W_{oil} and W_{SS} are the weight of input oil and SS in artificial wastewater, respectively.

$$R = \frac{\Delta W_m}{W_{oil} + W_{SS}} \tag{1}$$

In this simulation, the recovery rate of SS recovery equipment was measured for a mixture of oil and SS, because it is difficult to separate oil and SS perfectly. However, recovered SS could be used as a valuable resource if SS recovery equipment could separate oil and SS perfectly that would decrease the amount of SS and the treatment costs.

Drinking water as a base solvent was heated to 20 °C to represent ordinary wastewater and to 60 °C to represent hot wastewater for the investigation of the effect of wastewater heating. The process of creating artificial wastewater is described in **Fig. 3**; 1 L of drinking water was heated to the target temperature. The appropriate
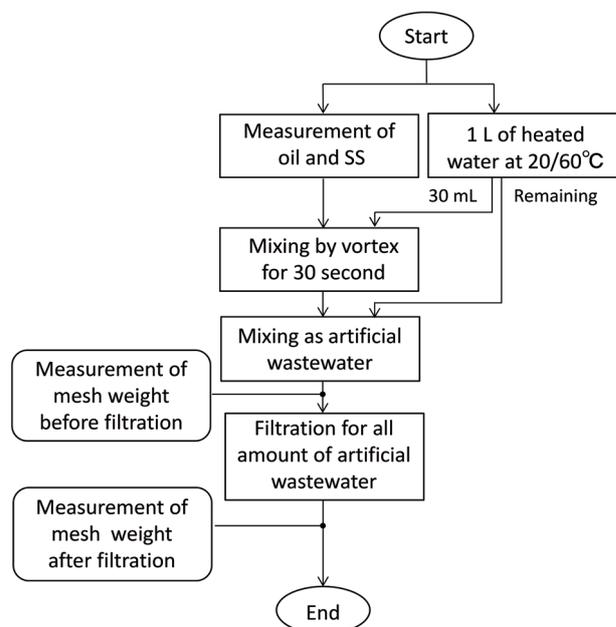
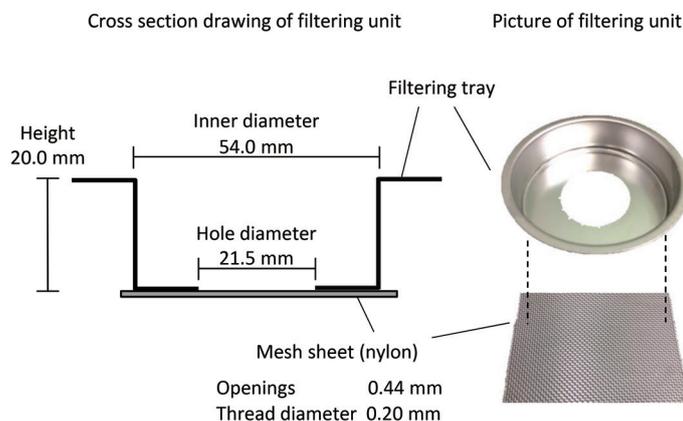Fig. 3 Procedure of filtration experiments including the preparation of artificial wastewater

Fig. 2 Filtration unit used in filtration experiments

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concentrations of sunflower oil and flour were measured and put into a centrifuge tube. Heated drinking water (30 mL) was added to the tube, which was stirred by a vortex mixer for 30 s. The stirred mixture and the remaining heated drinking water were added to a mixing container to create artificial wastewater. Filtration through the mesh sheet was conducted immediately before artificial wastewater could settle out as sediment.

2.2　Evaluation of oil-water separation and SS recovery

Wastewater from the model restaurant included vegetable oil and food residue such as protein, representing oil and SS in the filtration experiments, respectively. The amount of wastewater released from the restaurant was 3 m^3/day, the concentration of n-hexanes that represented oil concentration was 19,000 mg/L, and SS concentration was 1,100 mg/L.

Fig. 1 shows the concept of the oil-water separation and SS recovery equipment in a restaurant. The oil-water separation equipment separates recovered oil and oil-removed water midstream from the oil- and SS-containing wastewater upstream. The SS recovery equipment separates the recovered SS and oil- and SS-removed water downstream from the oil-removed water midstream. The economic value of the recovered oil, the recovered SS, the oil- and SS-removed water, and the oil- and SS-containing wastewater depends on their volumes and purity (concentration) levels.

Based on a previous study [9] where W_{in} [kg/day], O_{out} [kg/day], S_{out} [kg/day], and W_{out} [kg/day] are the amount of the oil- and SS-containing wastewater per day, the recovered oil per day, the recovered SS per day, and the oil- and SS-removed water per day, respectively. $X_{W/Win}$ [-], $X_{W/Oout}$ [-], $X_{W/Sout}$ [-], and $X_{W/Wout}$ [-] are defined as the water mixing ratios in: the oil- and SS-containing wastewater, the recovered oil, the ecovered SS, and the oil- and SS-removed water, respectively. $X_{O/Win}$ [-], $X_{O/Oout}$ [-], $X_{O/Sout}$ [-], and $X_{W/Oout}$ [-] are defined as the oil-mixing ratios in: the oil- and SS-containing wastewater, the recovered oil, the recovered SS, and the oil- and SS-removed water, respectively. $X_{S/Win}$ [-], $X_{S/Oout}$ [-], $X_{S/Sout}$ [-], and $X_{S/Oout}$ [-] are defined as the SS mixing ratios in: the oil- and SS-containing wastewater, the recovered oil, the recovered SS, and the oil- and SS-removed water, respectively. The relationship between these variables is expressed by the following equations.

$$W_{in} = O_{out} + S_{out} + W_{out} \tag{2}$$

$$O_{out} \cdot X_{i/Oout} + W_{out} \cdot X_{i/Sout} + W_{out} \cdot X_{i/Wout} = W_{in} \cdot X_{i/Win} \tag{3}$$

$$X_{W/j} + X_{O/j} + X_{S/j} = 1 \tag{4}$$

where i = W, O, S and j = W_{in}, O_{out}, W_{out} are assumed to be true.

2.3　Value Function and Separative Work Unit

The SWU is a scale of treatment ability of a separation process and is widely used in the field of nuclear power engineering amongst others [11] ~ [13]. A value function (VF) is used to calculate SWU and to convert concentration X to an economic value. SWU is equal to the difference between the total economic value of each substance obtained after separation and the value of mixture before separation. In this study, SWU is considered as the difference between total economic value of the oil-removed water, the recovered oil, and the recovered SS and of the oil- and SS-containing wastewater. Each economic value was calculated by multiplying VF [JPY/kg] by the amount of target substance [kg].

Based on a previous study [9], the VF of oil-water separation and SS recovery in the model restaurant should be defined for each product with a single unit. Then, $f(X_{O/Oout})$ [JPY/kg], $g(X_{W/Wout})$ [JPY/kg], $i(X_{S/Sout})$ [JPY/kg], and $h(X_{W/Win})$ [JPY/kg] are assumed to be the VFs of the recovered oil, the oil- and SS-removed water, the recovered SS, and the oil- and SS-containing wastewater, respectively. The VFs were determined based on the field investigation at a food processing factory, restaurant, and food shops. The initial and running costs of the oil-water separation and SS recovery equipment were included in $g(X_{W/Wout})$, the VF of the oil- and SS-removed water.

Daily SWU in the model restaurant, δU_{ss}, was defined by eq. (5). A positive value of δU_{ss} means that profit is generated by separation and a negative value indicates that a cost is incurred by separation.

$$\delta U_{ss} = O_{out} \cdot f(X_{O/Oout}) + W_{out} \cdot g(X_{W/Wout})$$
$$+ S_{out} \cdot i(X_{S/Sout}) - W_{in} \cdot h(X_{W/Win}) \tag{5}$$

In this study, two cases of an economic evaluation were calculated: δU_{ss}, where the model restaurant installed both oil-water separation and SS recovery equipment (SWU for combination use); and δU_s, where the model restaurant installed oil-water separation equipment without SS recovery equipment (SWU for single use) [9].

As the recovered oil is sold as fuel, the VF of the recovered oil, $f(X_{O/Oout})$, is determined by the heating value and is expressed as follows.

$$f(X_{O/Oout}) = V_{heat} \cdot (X_{O/Oout} \cdot H_{oil} + X_{S/Oout} \cdot H_{SS} - X_{W/Oout} \cdot H_{wat}) \tag{6}$$

where V_{heat} [JPY/J] is the conversion factor from the heating value to the economic value. H_{oil} [J/kg] and H_{SS} [J/kg] are the heating values of oil and SS, and H_{wat} [J/kg] is the heat of vaporization for water.

In some cases, the recovered SS can be collected as a valuable resource. However, this study assumed that the recovered SS was collected as industrial waste because it also included oil. Below 85% water content, the collecting

cost represented the VF of the recovered SS, $i(X_{S/Sout})$ [JPY/kg], was determined by the amount of industrial waste, as follows.

$$i(X_{S/Sout}) = -C_{ind} \qquad (7)$$

where C_{ind} [JPY/kg] is the collecting cost of the industrial waste.

Wastewater treatment facility treats some components such as BOD, COD, n-hexanes, SS, T-N, and T-P at the same time [14]. The initial cost, the running cost, and the size of a wastewater treatment facility were determined by the type and amount of these components in wastewater [7]. Especially, n-hexanes as oil influence the cost and the size of a wastewater treatment facility [15]. The initial and running costs of a wastewater treatment facility are traditionally determined by the daily allowable amount of wastewater because the treatment facility can only treat oil- and SS-free or low oil- and SS-containing wastewater, rather than wastewater containing high levels of oil as in the case of the model restaurant. Therefore, the standard costs of a wastewater treatment facility for oil- and SS-containing wastewater are not clear but can be determined by a facility scale for the maximum permissible concentrations of n-hexanes as oil, N [kg/L], and of SS, NSS [kg/L] (eqs. (8) and (9)).

$$P_i = p_i \cdot \frac{a}{A \cdot N} \cdot \frac{b}{A \cdot N_{SS}} = p_i \cdot \frac{a}{N} \cdot \frac{b}{N_{SS}} \cdot \frac{1}{A^2} \qquad (8)$$

$$P_r = p_r \cdot \frac{a}{A \cdot N} \cdot \frac{b}{A \cdot N_{SS}} = p_r \cdot \frac{a}{N} \cdot \frac{b}{N_{SS}} \cdot \frac{1}{A^2} \qquad (9)$$

where P_i [JPY/L] is the initial cost and P_r [JPY/L] is the running cost of a wastewater treatment facility that should treat wastewater containing oil and SS, respectively. p_i [JPY/L] and p_r [JPY/L] are the standard initial and running costs, respectively, of a wastewater treatment facility for the total amount of wastewater treated over the lifetime of the facility. In eqs. (8) and (9), $a/A > N$ and $b/A > N_{SS}$ are assumed to be true and a [kg/day], b [kg/day], and A [L/day] are the amounts of oil and SS in the oil- and SS-containing wastewater per day, and the volume of the oil- and SS-containing wastewater per day, respectively.

Recovering oil and SS from wastewater contributes to the reduction in the cost of a wastewater treatment facility. $h(X_{O/Win})$ [JPY/kg] in eq. (10) represents the VF for the oil- and SS-removed water and consists of the initial and running costs of the wastewater treatment facility without any oil-water separation and SS recovery equipment. $g(X_{O/Wout})$ [JPY/kg] in eq. (11) represents the VF for the oil- and SS-containing wastewater and consists of the initial and running costs of a wastewater treatment facility with an oil-water separation and SS recovery equipment. Then $g(X_{O/Wout})$ [JPY/kg] was determined by adding the initial and running

costs of the oil-water separation and SS recovery equipment to $h(X_{O/Win})$ [JPY/kg]. $h(X_{W/Win})$ [JPY/kg] and $g(X_{W/Wout})$ [JPY/kg] were calculated by using eq. (3).

$$h(X_{O/Win}) = -\frac{P_i + P_r}{\rho} = -\frac{(p_i + p_r) \cdot \rho}{N \cdot N_{SS}} \cdot \frac{a}{A\rho} \cdot \frac{b}{A\rho}$$

$$= -\frac{(p_i + p_r) \cdot \rho}{N \cdot N_{SS}} \cdot X_{O/Win} \cdot X_{S/Win} \qquad (10)$$

$$g(W_{O/Wout}) = h(X_{O/Wout}) - \frac{P_{sep\text{-}oil} + P_{rec\text{-}SS} + (E_{sep\text{-}oil} + E_{rec\text{-}SS}) \cdot \eta}{\rho} \qquad (11)$$

where, ρ [kg/L] is the density of wastewater that changes with $X_{O/Win}$. $P_{sep\text{-}oil}$ [JPY/L] and $P_{rec\text{-}SS}$ [JPY/L] are the initial costs of oil-water separation and SS recovery equipment, respectively, for the amount of wastewater treated over the lifetime of the equipment. $E_{sep\text{-}oil}$ [kWh/L] and $E_{rec\text{-}SS}$ [kWh/L] are the input energy (electricity) of oil-water separation and SS recovery equipment, respectively, for the total amount of treated wastewater over the lifetime of the equipment. η [JPY/kWh] is the conversion factor between cost and energy.

The field investigation data used to calculate SWU in the model restaurant are shown in **Table 1**. The initial cost of oil-water separation and SS recovery equipment included the product cost without the cost of installation. The running cost of oil-water separation and SS recovery equipment included the maintenance cost without the labor cost. Each initial cost was determined as one-tenth of the cost of the equipment installed on the actual factory because the treatment amount of wastewater in the model restaurant (3,000 L/day) was one-tenth of the actual factory capacity. The running cost of oil-water separation equipment was assumed to be same with the cost of the actual factory. The running cost of SS recovery equipment was 0 JPY/month because the equipment was the filtration mesh that required no electricity or maintenance material.

Calculations were conducted by changing the separation ability of oil-water separation equipment. The recovery rate of SS recovery equipment was determined based on the results of the filtration experiments. Finally, all parameters regarding the oil- and SS-containing wastewater, the recovered oil, the recovered SS, and the oil- and SS-removed water were automatically determined based on the separation ability of oil-water separation equipment and the recovery rate of SS recovery equipment.

3. Results and Discussion

3.1 Relationship between oil concentration rate of artificial wastewater and recovery rate of oil and SS by filtration

Fig. 4 shows the viscosity of artificial wastewater with only sunflower oil with changing oil concentrations

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Table 1 Specific data for calculating Separative Work Unit (SWU) in model restaurant

Variable	Value	Unit
Heating value of fuel oil A	39.1 [16]	MJ/L
Price of fuel oil A	90.7 [17]	JPY/L
V_{heat}	0.00000232	JPY/J
Heating value of sunflower oil	9,200 [18]	kcal/kg
H_{oil}	37,656,000	J/kg
H_{wat}	2,270,000 [19]	J/kg
a	57*	kg/day
b	3.3*	kg/day
A	3,000*	L /day
N	0.00003 [20]	kg/L
N_{SS}	0.00016 [20]	kg/L
$P_{sep-oil}$	0.0791*	kWh/L
$E_{sep-oil}$	0.000030*	kWh/L
P_{rec-SS}	0.000244*	kWh/L
E_{rec-SS}	0*	kWh/L
H	17.08 [21]	JPY/kWh
Specific gravity of vegetable oil	0.915 [22]	-
Specific gravity of water	1	-
Specific gravity of SS	1.6 [23]	-
Wastewater treatment facility		
Lifetime	15*	year
Initial cost	6,000,000*	JPY
Running cost	30,721*	JPY/month
Oil-water separation equipment		
Lifetime	15*	year
Initial cost	1,300,000*	JPY
Running cost	1.35*	JPY/month
SS recovery equipment		
Lifetime	15*	year
Initial cost	4,000*	JPY
Running cost	0*	JPY/month

Values marked * were obtained through field investigations

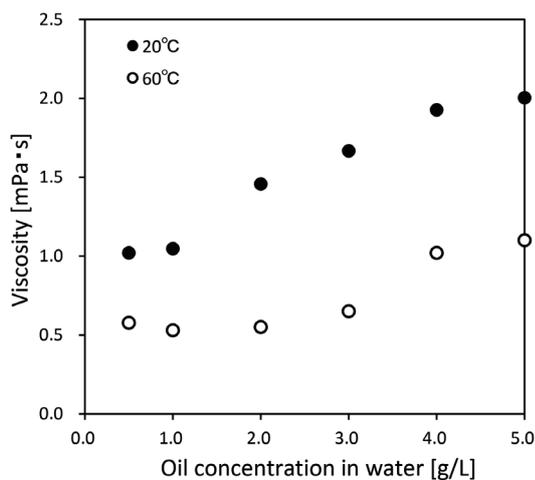
Fig. 4 Viscosity of artificial wastewater with changing oil concentrations used in the filtration experiments at 20 °C and 60 °C

at 20 °C and 60 °C. **Fig. 5** shows the viscosity of artificial wastewater with only flour as SS with changing SS concentrations at 20 °C and 60 °C. Although the viscosity of artificial wastewater with SS was almost constant regardless of the SS concentration, the viscosity of artificial wastewater with oil gradually increased with increasing oil concentration in wastewater. This result suggests that oil concentration in water has a greater effect on the viscosity of wastewater than the SS concentration. Moreover, higher water temperatures were associated with lower viscosity values.

One of results of the filtration experiments with artificial wastewater at 20 °C and with 0.5 g/L of oil concentration are shown in **Fig. 6**. Although artificial wastewater was assumed to be the oil-removed wastewater,
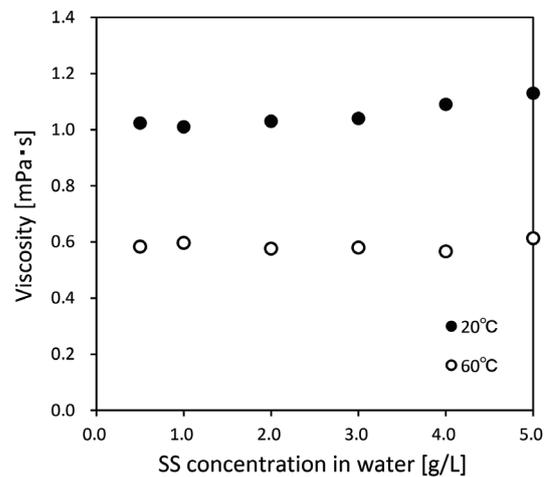

Fig. 5 Viscosity of artificial wastewater with changing SS concentrations used in the filtration experiments at 20 °C and 60 °C
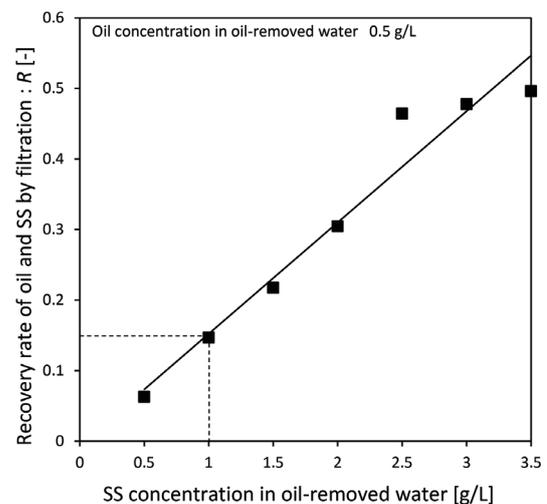

Fig. 6 Relationship between SS concentration in oil-removed water and recovery rate of oil and SS by filtration: R [-] (20 °C; oil concentration in oil-removed water 0.5 g/L)

Table 2 Values of fitted curves elucidated by the filtration experiments with artificial wastewater at 20 ℃ and 60 ℃

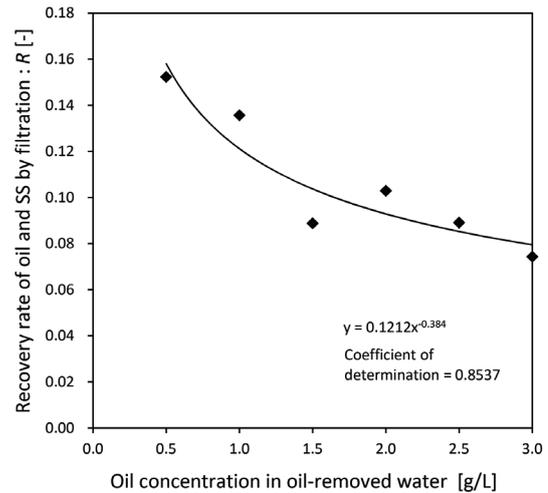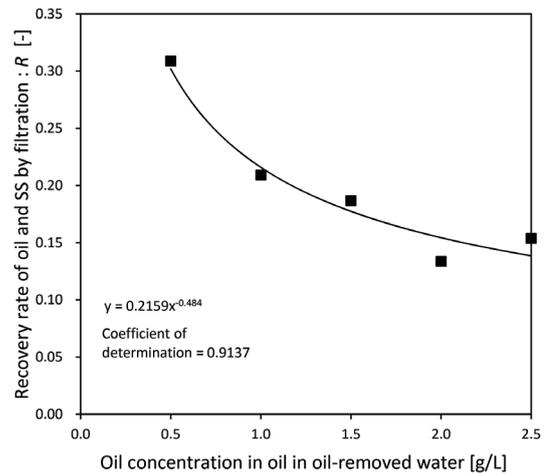| Oil concentration in oil-removed water [g/L]	Fitted curve	Coefficient of determination
20 ℃: Temperature of artificial wastewater		
0.5	$y = 0.1577x - 0.0054$	0.9524
1.0	$y = 0.1117x + 0.024$	0.8660
1.5	$y = 0.0707x + 0.0181$	0.8218
2.0	$y = 0.0280x + 0.0749$	0.7375
2.5	$y = 0.0381x + 0.051$	0.7573
3.0	$y = 0.0603x + 0.014$	0.9537
60 ℃: Temperature of artificial wastewater		
0.5	$y = -0.0048x + 0.3135$	0.0089
1.0	$y = 0.0751x + 0.1339$	0.7989
1.5	$y = 0.0717x + 0.1149$	0.8599
2.0	$y = 0.0785x + 0.0551$	0.5120
2.5	$y = 0.0235x + 0.1302$	0.4965
3.0	$y = 0.0335x + 0.0918$	0.7939

x: SS concentration in oil-removed water [g/L]

y: Recovery rate of oil and SS by filtration: R [-]

depending on the separation ability of oil-water separation equipment, residual oil concentration in wastewater was determined. Then, the filtration experiments were conducted for each residual oil concentration in wastewater. Fitted curves explained the relationship between the SS concentration in artificial oil-removed wastewater and the recovery rate of oil and SS by filtration (R [-]: defined in eq. (1)). Other results of the filtration experiments at 20 ℃ and 60 ℃ are listed in Table 2. Under all oil concentrations (0.5-3.0 g/L), R [-] linearly increased at higher SS concentrations. Here, 0.318 of R [-] was achieved as the average value at 60 ℃, 0.5 g/L of n-hexanes extract, and 0.5 g/L of SS by using actual wastewater from the cafeteria of the University of Tsukuba in December 2016. n-hexanes and SS concentration were measured once every hour for three hours, and R [-] was measured from the result of the nine filtration experiments. Compared to this result, the value of R [-] by artificial wastewater (at 60 ℃, 0.5 g/L of oil concentration) calculated as 0.311 from Table 2 was enough close.

In the model restaurant, oil concentration in the oil-removed water was 1 g/L (1 g of oil per 1 L of water). Thus, R [-] based on the oil concentration of 1 g/L after the oil removal was chosen to explain the relationship between the oil concentration in the oil-removed water and R [-] at 20 ℃ (Fig. 7) and 60 ℃ (Fig. 8). R [-] at 20 ℃ and 60 ℃ decreases with increasing oil concentration in the oil-removed water. This result suggests that high SS recovery performance by filtration can be obtained by reducing the oil concentration in wastewater. Increasing oil concentration in the oil-removed water inhibited the collection of SS on the mesh

Fig. 7 Oil concentration in oil-removed water and recovery rate of oil and SS by filtration: R [-] (20 ℃) (SS concentration 1 g/L)

Fig. 8 Oil concentration in oil-removed water and recovery rate of oil and SS by filtration : R [-] (60 ℃) (SS concentration 1 g/L)

because SS were wrapped in oil and passed through the mesh with the oil due to its high viscosity.

3.2 Separation ability of oil-water separation and the recovery rate of SS recovery equipment

By changing the separation ability of oil-water separation equipment from 0 to 100% in steps of 5%, the oil concentration in the oil-removed water was determined. Based on this concentration and the results of Figs. 7 and 8, R [-] in SS recovery equipment downstream of oil-water separation equipment was determined. Fig. 9 shows the relationship between the separation ability of oil-water separation equipment and R [-] in SS recovery equipment with wastewater at 20 ℃ and 60 ℃. Here, R [-] described in eq. (1) was equal to the recovery rate of SS recovery
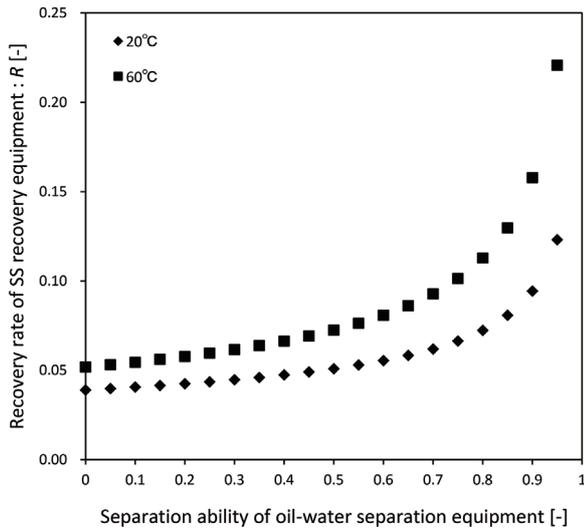
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Fig. 9 Separation ability of oil-water separation equipment and recovery rate of SS recovery equipment: R [-]

Fig. 10 Relationship between separation ability of oil-water separation equipment and SWU for combination and single use at 20 °C
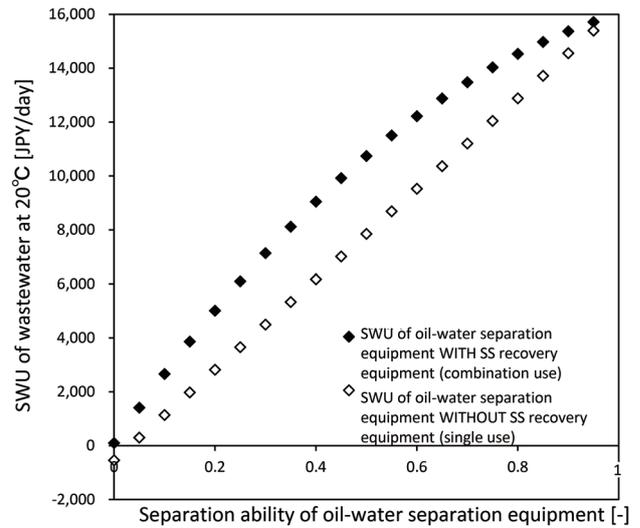

Fig. 11 Relationship between separation ability of oil-water separation equipment and SWU for combination and single use at 60 °C

equipment.

At both 20 °C and 60 °C, R [-] exponentially increases with higher separation ability of oil-water separation equipment. SS recovery equipment with low input energy and high recovery rate can be developed. Decreasing the mesh opening size would increase R [-], but can lead to increased clogging of the mesh. A proper size of the mesh opening should be selected for each restaurant, to enable low maintenance costs and sustainable use of SS recovery equipment.

R [-] of wastewater at 60 °C was higher than that at 20 °C. The difference in R [-] between 20 °C and 60 °C increases with higher separation ability of oil-water separation equipment. Therefore, from the viewpoint of recovering oil and SS by filtration equipment, heating wastewater is an effective way of increasing the recovery rate of SS recovery equipment and decrease the contaminants in the treated water.

3.3 Trial calculation of SWU

The relationship between the separation ability of oil-water separation and the recovery rate of SS recovery equipment from the results of our filtration experiments was used to calculate the SWU for combination use at 20 °C (Fig. 10) and 60 °C (Fig. 11). The SWU for single use is also shown in Figs. 10 and 11.

At 20 °C and 60 °C, the SWU for single use increases linearly with the increasing separation ability of oil-water separation equipment. However, the SWU for combination use increases logarithmically with the increasing separation ability. Regardless of the separation ability of oil-water separation equipment, the SWU for combination use is
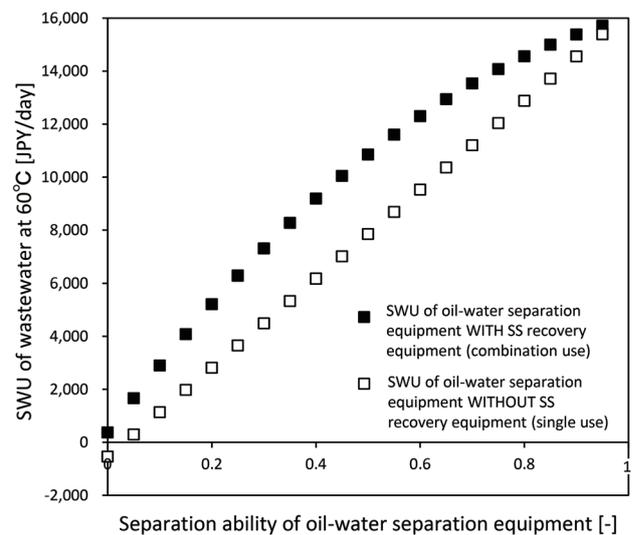
always higher than that for single use.

At 0% separation ability, the SWU for single use is negative, meaning that installing oil-water separation equipment would be economically undesirable. Above 5% separation ability, the SWU for single use becomes positive indicating that even with low separation ability, installing oil-water separation equipment would be economically feasible. On the other hand, the SWU for combination use is positive for all separation ability value.

In addition, Fig. 12 illustrates the relationship between the separation ability of oil-water separation equipment and the difference in the SWU between combination and single uses that shows the effectiveness
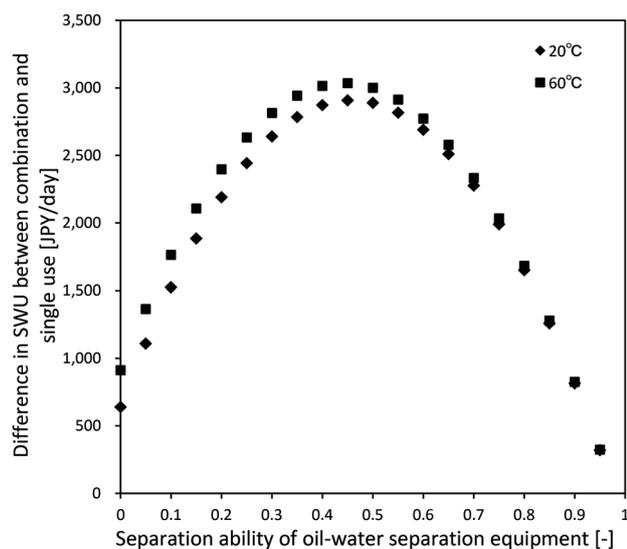
Fig. 12   Separation ability of oil-water separation equipment and difference in SWU between combination and single uses

Fig. 13   Separation ability of oil-water separation equipment and difference in SWU for combination use between 20 °C and 60 °C

of adding SS recovery equipment downstream of oil-water separation equipment (maximum value on 45% separation ability, 539 JPY/day at 20 °C and 562 JPY/day at 60 °C). The difference decreases toward 0% and 95% separation abilities. The minimum difference at 95% separation ability was 58 JPY/day at both 20 °C and 60 °C.

At both 20 °C and 60 °C, the difference between the SWU for combination and single uses is positive, meaning that installing both oil-water separation and SS recovery equipment has a positive economic effect.

Fig. 13 shows the relationship between the separation ability of oil-water separation equipment and the difference in the SWU for combination use at 20 °C and 60 °C that shows the effectiveness of heating wastewater. The difference decreases with increasing the separation ability of oil-water separation equipment. The maximum difference in the SWU for combination use at 20 °C and 60 °C is 273 JPY/day at 0% separation ability and the minimum is 11 JPY/day at 95% separation ability.

Increasing the wastewater temperature from 20 °C to 60 °C did not change the SWU significantly if the separation ability of oil-water separation equipment was maintained. However, regardless of the separation ability, the difference in the SWU between combination and single uses is positive, meaning that heating wastewater is economically feasible.

At the actual factory, wastewater that flowed into oil-water separation equipment was at a temperature of about 60 °C and thus it needed not be heated before treatment. In general, the recovery rate of oil and SS in wastewater from factories can be improved by heating wastewater upstream before releasing it into a wastewater treatment facility.
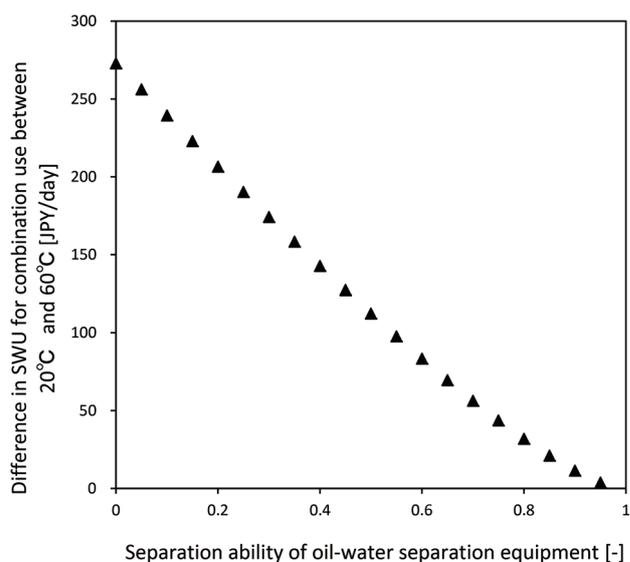
In this study, the effect of the SWU on installing

both oil-water separation and SS recovery equipment (combination use) was not high because the amount of wastewater was relatively small. If the relationship between the oil concentration in the oil-removed water and the recovery rate of oil and SS by filtration, R [-], such as in Figs. 7-9, is applied to animal fat instead of vegetable oil, the SWU of food processing factories, restaurants, and food shops that discharged a large amount of wastewater would be significantly greater. This is because the profit from increasing the amount of the recovered oil and decreasing wastewater treatment costs would be larger than the initial and running costs of installing oil-water separation and SS recovery equipment.

4.   Conclusions

1) To explain the effect of installing oil-water separation and SS recovery equipment for wastewater treatment at a restaurant or food shop, an economic evaluation by SWU was conducted for two cases: using oil-water separation equipment without SS recovery equipment (single use) and using oil-water separation equipment with SS recovery equipment (combination use).

2) Filtration experiments with artificial wastewater explained the relationship between the input amount of SS in the oil-removed water and the recovery rate of oil and SS by filtration, R [-], at 20 °C and 60 °C. The separation ability of oil-water separation equipment could determine the required R [-] of SS recovery equipment.

3) The SWU for combination use at 20 °C and 60 °C was higher than the SWU for single use. The SWU for combination use at 60 °C was higher than that at 20 °C.

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At 60 °C, combination use increased the SWU by 562 JPY/day compared to single use, at 45% separation ability of oil-water separation equipment according to the results of our filtration experiments.

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