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Direct membrane filtration of municipal wastewater with chemically enhanced backwash for recovery of organic matter



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HIGHLIGHTS

- Organic matter in municipal wastewater was recovered by direct membrane filtration.
- Chemically enhanced backwash (CEB) was very effective in controlling membrane fouling.
- Selection of reagents used for CEB influenced recovery of organic matter.
- Feasibility of direct membrane filtration of municipal wastewater was clearly shown.

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ABSTRACT

Direct membrane filtration (DMF) of municipal wastewater using a microfiltration membrane was investigated to capture organic matter. In contrast to the expectation that membrane fouling cannot be controlled in DMF of domestic wastewater, it was possible to stably continue membrane filtration with relatively high membrane fluxes (~20 LMH) for >200 h by applying chemically enhanced backwash (CEB), whereas approximately 75% of the organic matter in wastewater could be recovered. Off-line chemical membrane cleaning could completely restore membrane permeability, indicating the possibility of a much longer operation of DMF. Selection of chemical reagents used for CEB was found to influence the amount of organic matter recovered by DMF. Based on the experimental results, feasibility of DMF was discussed by a comparison with a conventional wastewater treatment plant treating the same wastewater as studied in this study.

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1. Introduction

A huge amount of energy is used for wastewater treatment. Total energy consumption of sewage treatment plants in Japan was about 7 trillion Watts hour in 2004, accounting for approximately 0.7% of total national energy consumption ([Japan for sustainability, 2008](#)). In the USA, energy used for wastewater treatment accounts for about 3% of the national electric energy load ([McCarty et al., 2011](#)). [Mizuta and Shimada \(2010\)](#) reported that specific energy consumption of conventional activated sludge plants without sludge incineration is in the range between 0.3 and 1.89 kWh/m³. A large portion of the energy consumed in

wastewater treatment is used for aeration, which is necessary for microbial degradation of organic matter in wastewater.

Organic matter in raw wastewater is partially converted to biomass, which is eventually used for biogas production (energy recovery) in some cases. However, the conversion rate to biomass is not high ([Rittmann and McCarty, 2001](#)). At present, a large portion of organic matter in wastewater is not recovered but is degraded into carbon dioxide and water with external energy input. A paradigm shift is necessary: organic matter in wastewater should not be degraded but recovered for energy production. Wastewater from domestic usage contains a significant amount of potential energy ([Heidrich et al., 2011](#)). Capturing this organic matter as a renewable energy source will be an attractive process ([Sutton et al., 2011](#)). Wastewater treatment plants can be net energy producers by utilizing organic matter in municipal wastewater that is currently degraded with external energy input ([McCarty et al., 2011](#)).

Anaerobic treatment processes are viable options for producing energy from organic matter in wastewater. Concentration of COD in municipal wastewater is in the range of 250–800 mg/L ([Metcalf and Eddy, 2003](#)), whereas it is difficult to apply anaerobic

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processes to wastewater with COD concentrations of <1500–2000 mg/L (Metcalf and Eddy, 2003). Concentrating raw wastewater can therefore facilitate application of anaerobic processes to produce biogas. Analysis of the particle size distribution of organic matter in raw municipal wastewater showed that 63–70% of total organic carbon (TOC) was associated with particles that were larger than 0.1 μm (Levine et al., 1985). Loose membranes such as microfiltration (MF) membranes can efficiently retain particulate and colloidal organic matter in wastewater. Concentrating organic matter in wastewater can therefore be carried out by membrane processes, facilitating recovery of energy from wastewater via anaerobic digestion. Direct membrane filtration (DMF) of wastewater has advantages including simplicity of design and maintenance (Ravazzini et al., 2005). However, in DMF of municipal wastewater, severe membrane fouling is very likely to occur. Although several attempts have been made to concentrate organic matter in wastewater by using membranes (Ravazzini et al., 2005; Hernandez Leal et al., 2010; Mezohegyi et al., 2012), few studies have focused on membrane fouling in DMF. It is not clear whether long-term operation of a membrane process for recovery of organic matter from wastewater is feasible.

Recent developments and modifications in manufacturing have made membranes much more robust, enabling chemically enhanced backwash (CEB) to be carried out in routine operations. In CEB, a chemical cleaning reagent is added to the backwash solution and cleaning efficiency is significantly improved. CEB is popularly used in controlling membrane fouling in both traditional membrane filtration processes or membrane bioreactor (MBR) systems (Zheng et al., 2011). Intensive CEB, in terms of both frequency and concentration of the chemical reagent, may enable long-term operation of DMF of municipal wastewater. There have been few attempts to examine CEB in DMF of municipal wastewater. The objective of this study was therefore to investigate the feasibility of DMF of municipal wastewater with CEB.

2. Methods

2.1. Membrane filtration unit

A schematic representation of the laboratory-scale filtration setup used in this study is shown in Fig. 1. It consisted of two filtration tanks (designated T1 and T2 hereafter) with an effective volume of 0.75 L each. Hollow-fiber MF membranes made from poly-vinylidene fluoride (PVDF) polymer (Asahi Kasei Chemicals, Tokyo, Japan) were used in this study. Nominal pore size of the membranes used was 0.1 μm . Mini-membrane modules were assembled in the laboratory. Areas of membrane surface immersed in T1 and T2 were 0.1 and 0.03 m^2 , respectively.

Raw wastewater collected daily from the inlet of the primary sedimentation tank of Soseigawa Wastewater Treatment Plant, Sapporo, Japan was supplied as feed water in this study. The sewer system connected to the treatment plant is a combined system and covers a population of 200,000. Raw wastewater was firstly concentrated by membrane filtration in T1 and the retained organic matter was then delivered to T2 for further reduction of the volume of organic slurry (i.e., the final product that can be used for energy production).

Membrane filtration was carried out in the outside-in mode at constant membrane fluxes. Membrane fluxes in T1 and T2 were fixed at 20.8 and 16.7 LMH, respectively. Resultant trans-membrane pressure (TMP) was recorded automatically by digital pressure meters. Intermittent filtration (3 min pause for every 12 min of filtration) was performed with peristaltic pumps. To mix the tanks, aeration was also provided in both tanks at the flow rate of 4 L/min throughout the experiments.

CEB was carried out for 30 s every 12 h of operation with a flux of 210 LMH. Pure water was mixed with sodium hypochlorite (NaOCl), sodium hydroxide (NaOH) or citric acid and was used for CEB. As a reference, backwash with pure water was also examined. Concentrations of NaOCl solution, NaOH solution and citric acid solution used in CEB were 0.1% (as free chlorine), 0.1% (w/v) and 0.2% (w/v), respectively. According to the manufacturer, the membrane examined in this study can be used with CEB being performed more than 100,000 times using NaOCl, which was examined in this study.

In this study, concentration factor was defined as the ratio of volume of total feed wastewater over volume of the final product. Two sets of experiments attempting different concentration factors (21 and 50) were carried out in the present study. In the operations in which a concentration factor of 21 was attempted, raw wastewater was concentrated by 3.7 times on a volumetric basis in T1 first and then by 5.6 times in T2. In the case of a concentration factor of 50, T1 concentrated raw wastewater by 5 times and T2 concentrated it by 10 times. Flow rates in the experimental system were constantly monitored and adjusted to the target values. Therefore, it was confirmed that the anticipated concentration factors were achieved in all tests. At the beginning of each continuous filtration, the two tanks were filled with raw wastewater. Membrane filtration was then continued for about 200 h unless TMP reached 45 kPa.

2.2. Assessment of the distribution of fouling resistance

At the termination of each filtration run, fouled membranes were taken out from the tanks and subjected to dead-end filtration tests using pure water. Pure water permeabilities of the fouled membranes were measured to investigate the distribution of fouling (i.e., reversible or irreversible fouling).

The fouled membranes were gently wiped with a soft sponge to remove deposits from the membrane surface. Pure water permeability of the wiped membrane was then measured. Restoration of pure water permeabilities achieved by wiping represents the degree of reversible fouling, whereas filtration resistance that remained after wiping represents the degree of irreversible fouling (Kimura et al., 2004). Conversion from pure water permeability to filtration resistance was made on the basis of Darcy's law:

$$J = \frac{\Delta P}{\mu R_t}$$

where R_t is total filtration resistance (m^{-1}), J is permeate flux ($\text{m}^3/\text{m}^2/\text{s}$), ΔP is TMP difference (Pa), and μ is viscosity of water (Pa s).

2.3. Analysis

Loose membranes such as MF membranes used in this study (pore size: 0.1 μm) are not expected to retain large amounts of nitrogen and phosphorus in municipal wastewater (Mezohegyi et al., 2012). Therefore, COD and TSS were focused on in the present study. The feed to both tanks, permeates from both tanks and the product from T2 were collected for COD measurements every 24 h of operation. COD was measured by the closed reflux colorimetric method (HACH, Loveland, USA) using a HACH spectrometer (DR2800). Samples for TSS and VSS measurements were collected every 48 h of operation. TSS and VSS were measured by the standard method (APHA et al., 2005). Analysis of organic matter using size exclusion chromatography with organic carbon detection (LC-OCD) (Huber et al., 2011) was also performed in this study.

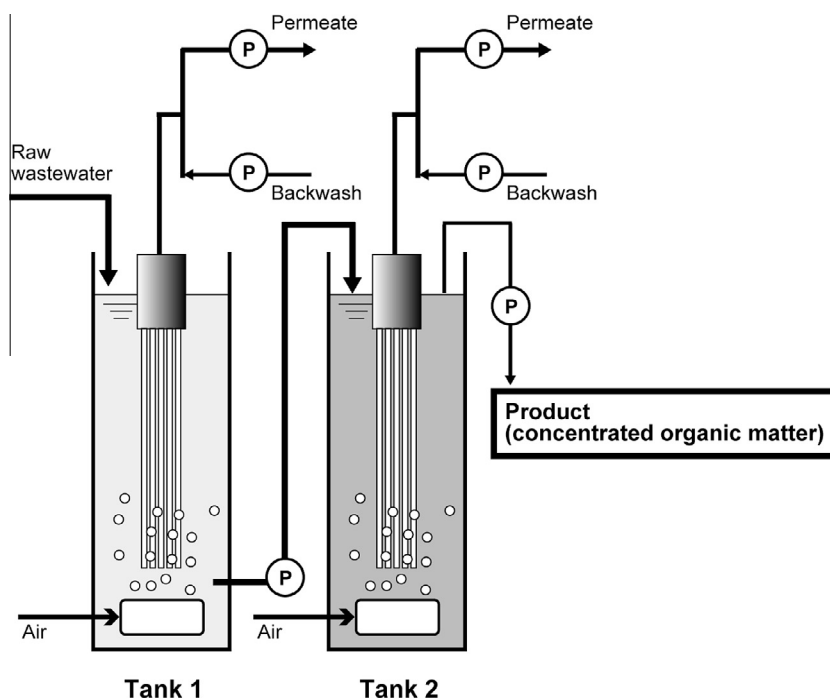


Fig. 1. Schematic diagram of the experimental set-up.

3. Results and discussion

3.1. Organic matter recovery

Concentrations of COD and TSS in the feed to T1 and T2, the product collected from T2 and the membrane permeates from both tanks are summarised in Table 1. COD concentration in the raw wastewater was approximately 240 mg/L. Concentration factor in the operation did not affect the concentration of COD in the permeate. However, the reagent used for CEB apparently affected COD concentration in the permeate. In the cases of pure water backwash and CEB with NaOH or citric acid, COD concentrations in T1 permeates and T2 permeates were almost identical. In the case of CEB with NaOCl, however, permeates from T2 tended to exhibit a higher concentration of COD than did those from T1. This can probably be explained by oxidation of particulate/colloidal organic matter by NaOCl, as discussed later. COD concentrations in the products collected from T2 with concentration factors of 21 and 50 were 2500 mg/L and 5000 mg/L, respectively. COD concentrations of the product were in the range that is suitable for applica-

tion of anaerobic digestion (Tauseef et al., 2013). Information on TSS of the product is also shown in Table 1. More than 90% of TSS in the products consisted of VSS. A high VSS fraction in the product is also suitable for biogas production (Cao and Pawlowski, 2012) and microbial fuel cells (Behera et al., 2011; Mezohegyi et al., 2012), indicating a potential advantage of DMF of municipal wastewater for energy recovery.

An example of the accumulative amount of COD fed to the system is shown by black bars in Fig. 2. In the operation corresponding to the data shown in Fig. 2, concentration factor was set at 50 and citric acid was used for CEB. The accumulative amount of feed COD was estimated by multiplying the constant feed flow rate with the feed COD concentration measured constantly (every 24 h). Accumulative amounts of product COD and permeate COD were estimated by the same procedure as that for feed COD and are shown by white bars and hatched bars, respectively, in Fig. 2. The ratio of product accumulative COD to feed accumulative COD represents the recovery of organic matter. Based on data obtained up to 168 h, it seemed that recovery rate of organic matter was not so high, limited to approximately 45%. However, in the series of

Table 1
COD and TSS concentrations in the feed, products and permeates.*

Backwash solution	Concentration factor of 21		Concentration factor of 50		
	Pure water	NaOCl	NaOCl	NaOH	Citric acid
<i>COD concentrations (mg/L)</i>					
Feed to T1	301 ± 35	216 ± 33	187 ± 37	283 ± 20	293 ± 29
Feed to T2	747 ± 33	684 ± 120	650 ± 115	1013 ± 70	1079 ± 201
Product	2583 ± 399	2496 ± 567	3600 ± 903	5960 ± 954	6843 ± 1056
Permeate from T1	41 ± 13	46 ± 14	44 ± 12	31 ± 5	51 ± 19
Permeate from T2	44 ± 7	78 ± 21	87 ± 33	35 ± 5	46 ± 11
<i>TSS concentrations (mg/L)</i>					
Feed to T1	129 ± 27	100 ± 17	91 ± 11	135 ± 9	155 ± 27
Feed to T2	411 ± 35	371 ± 92	376 ± 97	611 ± 34	732 ± 155
Product	1522 ± 342	1290 ± 359	1852 ± 873	4117 ± 699	5236 ± 1141
Permeate from T1	0	0	0	0	0
Permeate from T2	0	0	0	0	0

* Values are shown as average values with standard deviation.

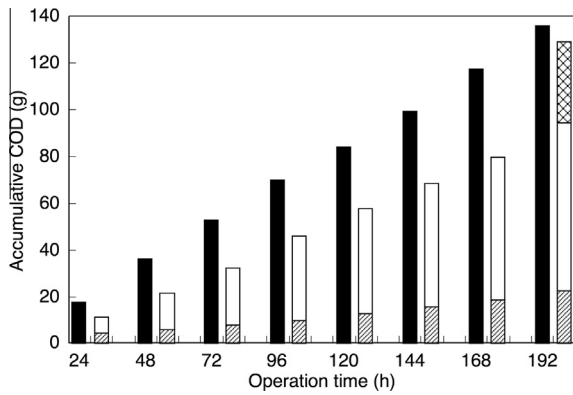


Fig. 2. An example of accumulative amount of feed COD (black bars), product COD (white bars) and permeate COD (hatched bars) in the operation with a concentration factor of 50 and CEB using citric acid. The cross-hatched bar represents COD of the deposit found on the inside walls of the tanks.

experiments, large amounts of particulate matter were deposited on the inside walls of both tanks. Contribution of these deposits to the total mass balance on COD would be negligible in the case of a large-scale and long-term operation. In the present study in which the tanks were small and the durations of operations were relatively short, the impact of the deposits on the mass balance was significant. Therefore, the deposits were manually scraped off at the termination of operations and were taken into consideration in the mass balances of COD. The contribution of the deposits is indicated by a cross-hatched bar in Fig. 2. The sum of product COD and deposit COD should represent the amount of organic matter that can be recovered by the proposed approach. About 75% of the organic matter in the raw wastewater was found to be recovered in this case. In Fig. 2, there is a difference between feed COD and the sum of permeate COD, product COD and deposit COD. This difference can be explained by biodegradation of organic matter, although retention times in both tanks were short.

COD mass balances estimated at the termination of each operation are shown in Fig. 3. Contribution of the deposit COD is included in these estimations. The size of each pie graph in Fig. 3 represents the accumulative COD fed to the system. Since real municipal wastewater was used in this study, COD concentrations examined in each experiment differed to some extent. Recovery of organic matter was generally high in this study: >70% recovery

could be achieved in the operations with CEB. In contrast, the operation with pure water backwash exhibited low recovery of organic matter (67%), which can be explained by loss due to biodegradation. Biodegradation also seemed to occur in the cases of CEB with NaOH and citric acid. In the case of operations with NaOCl backwash, however, biodegradation of organic matter was almost completely inhibited: the sum of accumulative product COD, accumulative permeate COD and deposit COD corresponded well to the accumulative feed COD. It should be pointed out that biodegradation could also have been avoided by eliminating aeration. Although aeration was provided for mixing the tanks in this study, it can be replaced with mechanical mixing.

3.2. Transformation of organic matter induced by CEB

In this study, transformation of organic matter was investigated by LC–OCD analysis. The peaks in an LC–OCD chromatogram can be assigned to biopolymers (e.g., polysaccharides and proteins), humics, building blocks and low molecular weight (LMW) acids and neutrals (Huber et al., 2011), as shown in Fig. S1 of the supporting information. As stated above, microbial activity in the experimental system was assumed in the operations with CEB using citric acid or NaOH. Slight increases of the signals for peaks of biopolymers, humics and LMW acid are seen in the permeates from T2 compared with the permeates from T1. This probably reflects biological production of those components occurring in T2. Biopolymers (i.e., polysaccharides and proteins) and humics are known to be major components of soluble microbial products (SMP) released during microbial metabolisms (Barker and Stuckey, 1999). LC–OCD chromatograms for the samples collected in the operation with CEB using NaOCl exhibited totally different features. Although microbial activities appeared to have been inhibited in the operations with NaOCl as suggested by the results shown in Fig. 3, the signal in the LC–OCD chromatogram for T2 became more significant than that in the LC–OCD chromatogram for T1. Additionally, new peaks appeared at retention times around 55 min in the chromatogram of T2 in the case of CEB using NaOCl. It should be noted that a very large peak seen in the NaOCl samples at a retention time of approximately 70 min was also seen with the raw wastewater (data not shown) for unknown reasons. Therefore, interpretation of the peak at retention time of 70 min was not attempted. It seems that the use of NaOCl degraded particulate/colloidal organic matter and resulted in an increase of dissolved organic matter,

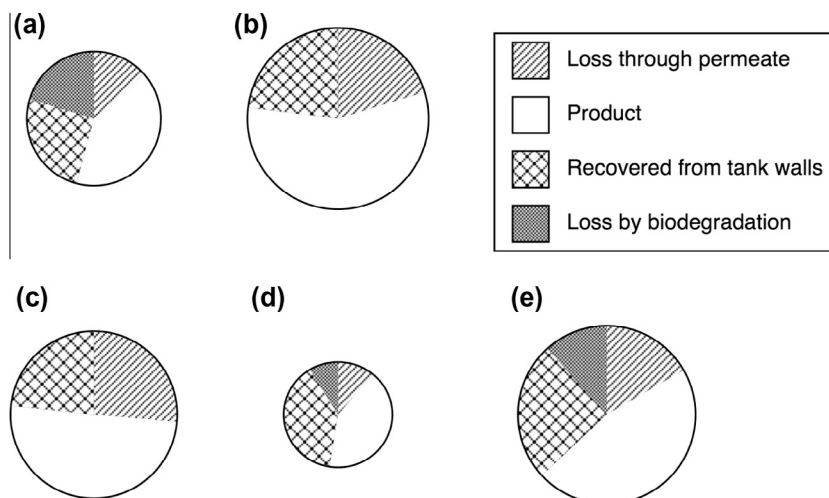


Fig. 3. Mass balances on COD in each operation: (a) pure water backwash with a concentration factor (CF) of 21, (b) CEB using NaOCl with CF of 21, (c) CEB using NaOCl with CF of 50, (d) CEB using NaOH with CF of 50, (e) CEB using citric acid with CF of 50.

which could penetrate the membrane. Increase of COD concentration in T2 permeates in the case of CEB using NaOCl (Table 1) supports this speculation. Selection of chemicals used for CEB is then difficult. The use of NaOCl for CEB can inhibit microbial activity and therefore can increase recovery of organic matter, but it may facilitate loss of organic matter via production of small organic molecules. The use of other chemicals may not result in production of such small molecules, but loss of organic matter due to microbial degradation is likely to occur, as suggested by the results shown in Fig. 3. Selection of chemicals used for CEB and adjustment of the concentration and/or frequency of CEB would maximise the organic recovery. Also, generation of chlorinated byproduct may limit the use of NaOCl for CEB. This aspect should be investigated in future research.

3.3. Membrane fouling in DMF of municipal wastewater

3.3.1. TMP profiles

Increases in TMP observed in the experiments examining concentration factor of 21 are shown in Fig. 4. In the operation in which backwash was carried out with pure water, very severe membrane fouling occurred. TMP in T1 increased very rapidly and reached a maximum pressure of 45 kPa within 96 h of operation. In contrast, membrane fouling was effectively mitigated in the operations in which NaOCl was used for CEB. TMP values in T1 were maintained below 30 kPa and the operations could be continued for more than 200 h. In T2, much lower TMP was observed, although concentrations of the feed were higher than those fed to T1 (see Table 1).

Increases in TMP observed in the experiments examining a concentration factor of 50 are also shown in Fig. 4. Despite the elevated concentration factors, increases of TMP were not so great with CEB using NaOCl. They were comparable to those observed with a concentration factor of 21. NaOCl could mitigate membrane

fouling in DMF of municipal wastewater even with the high concentration factor. In the operation with a concentration factor of 50, citric acid and NaOH were also examined as reagents for CEB. The effectiveness of NaOH was limited: TMP increased rapidly in T1 and reached a maximum value of 45 kPa within 70 h. In contrast, CEB with citric acid worked very efficiently and TMP increase was significantly suppressed. TMP increase with CEB using citric acid was comparable to that using NaOCl in T1. In T2, however, CEB using NaOCl exhibited less TMP increase than did CEB using citric acid. TMP increase in T2 with CEB using NaOCl was minimal, although concentration of the feed to T2 was high (see Table 1). In real conditions, pure water cannot be used for preparation of solutions for CEB. Care should be taken for consumptions of chemicals by impurities in water used for preparation of CEB solution.

Different chemical reagents have different effects for removing foulants from fouled membranes: it is generally thought that NaOCl (oxidizing reagent) is effective for removing organic matter from fouled membranes, whereas acids such as citric acid are effective for removing inorganic matter (Porcelli and Judd, 2010). It is notable that both NaOCl and citric acid were very effective for mitigation of membrane fouling in DMF of municipal wastewater. This implies that both organic matter and inorganic matter were involved in the evolution of membrane fouling in DMF of municipal wastewater. Alternative CEB using both NaOCl and citric acid would further mitigate membrane fouling in DMF of municipal wastewater.

The slow TMP increase in T2 might be explained by the lower applied membrane flux in T2 (Kimura et al., 2008). The data obtained in this study demonstrated that there is plenty of room for elevating membrane flux in T2, leading to more compact design of the system proposed and/or more elevated concentration factor of the product. The sizes of and membrane fluxes in each tank were determined on the basis of results of preliminary experiments in this study and were therefore not optimised. Balancing retention

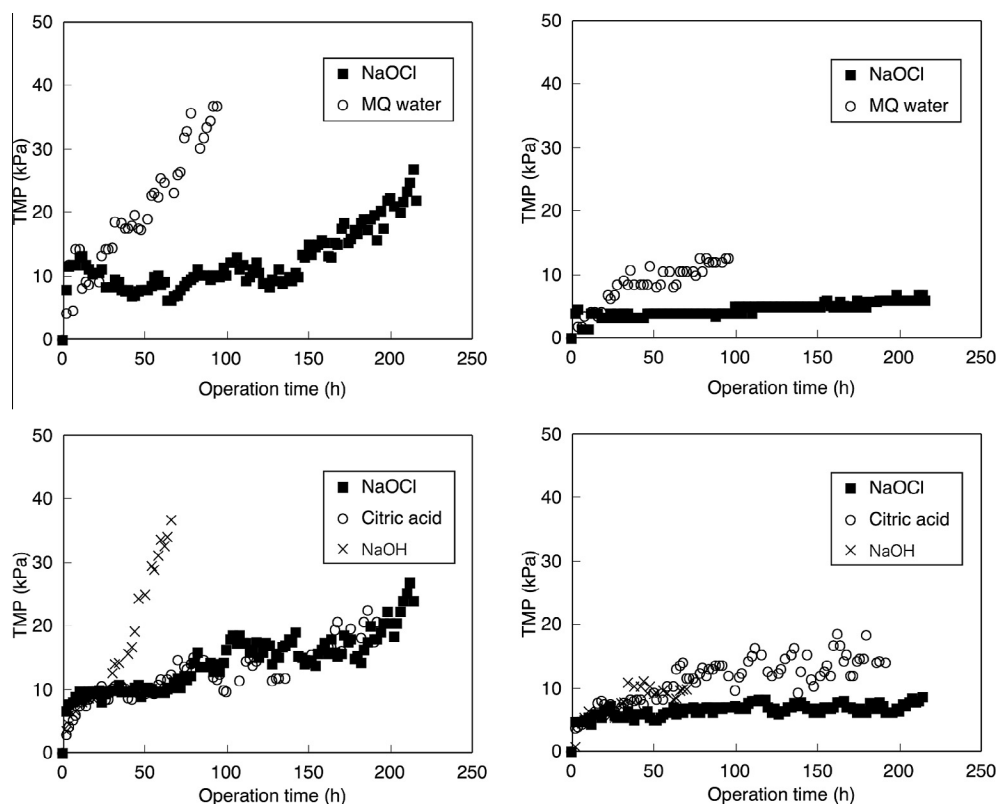


Fig. 4. TMP increases in T1 (left panels) and T2 (right panels) in the operations examining concentration factors of 21 (upper panels) and 50 (bottom panels).

time in each tank and membrane flux in both stages is certainly important. These are also important issues to be investigated in a future study.

3.3.2. Distribution of filtration resistances in fouled membranes

At the termination of each experiment, fouled membranes were subjected to dead-end filtration tests to measure filtration resistances and investigate the distribution of fouling resistances (i.e., reversible fouling versus irreversible fouling). Fig. 5 shows the degrees of reversible and irreversible filtration resistances assessed at the termination of the experiments examining a concentration factor of 50. As shown in the figure, reversible fouling was significant in all cases, clearly indicating plenty of room to improve the efficiency of the proposed system. Control of reversible fouling is not so difficult: increasing cross-flow velocity and/or introduction of granular materials in filtration tanks (Kimura et al., 2000; Siembida et al., 2010) would efficiently control the formation of cake layers. Hydraulic conditions in the two tanks used in this study (e.g., arrangement of the aerator) were not necessarily optimised. Increase of aeration rate would easily mitigate the formation of cake layers, though a large amount of electricity is needed. The aeration rate set in this study was low as aeration was done for mixing in the tanks, not for cleaning of membranes. It is possible to further mitigate reversible fouling in DMF of municipal wastewater by tuning hydraulic conditions, although the fouling observed in this study was not so severe.

Fig. 5 also shows that irreversible fouling was not efficiently controlled by citric acid, although overall membrane fouling was effectively mitigated by the reagent (Fig. 4). This means that citric acid was effective in preventing formation of cake layer on the membrane surface. It seems that inorganic matter played important roles in formation of the cake layer in this study. Fig. 5 also suggests that irreversible fouling in DMF of municipal wastewater was mainly caused by organic matter: NaOCl could effectively control the evolution of irreversible fouling. It has been suggested that transparent exopolymer particles (TEP), mainly produced by microalgae in natural environment, are major players in membrane fouling in a wide range of membrane filtration processes (Discart et al., 2013). This may be the case with DMF. CEB using NaOCl and citric acid alternatively would control membrane fouling in DMF of municipal wastewater very effectively. NaOCl would mitigate irreversible fouling, whereas citric acid would mitigate formation of the cake layer.

Off-line chemical cleaning of the fouled membranes (soaking in a chemical solution for 24 h) was carried out after assessment of irreversible fouling (i.e., after wiping with a sponge). Cleaning using NaOCl (0.1% as free chlorine) was followed by acid cleaning (mixture of 0.1% HCl (v/v) and 0.1% citric acid (w/v)). It should be noted that membrane permeabilities were almost completely re-

stored by the off-line chemical cleaning in all cases, strongly suggesting the feasibility of long-term stable operations of DMF.

3.4. Feasibility of the proposed DMF system

3.4.1. Potential energy production in DMF of municipal wastewater

Although microbial fuel cells have received much attention due to their theoretically high efficiency in energy production from organic matter, biogas (e.g., methane) production is still the most reliable and practical method for energy production from organic matter (McCarty et al., 2011). In this section, potential energy production by DMF of municipal wastewater is estimated on the basis of the data shown above, with the assumption that methane production via anaerobic digestion is used for electricity production.

Recent developments in anaerobic processes have improved specific biogas production (Bogte et al., 1993; Bodkhe, 2008; Tauseef et al., 2013). Electrical output of 1.5 kWh can be produced from 1 kg COD via methane production, with the assumption of 40% electric conversion (Van Lier, 2008). In the present study, it was demonstrated that approximately 5 kg of COD was recovered as the product from 50 m³ of the raw wastewater (see Table 1). Thus, with the assumption of 90% degradation of COD, electrical energy of 0.14 kWh can be generated from 1 m³ of the raw wastewater when DMF of municipal wastewater is implemented. It should be noted that the deposit COD found on inside walls of the tanks, which eventually should be included in the product in large-scale and long-term operation, was not included in this estimation of energy production. When the deposit COD was also included in the estimation of energy production from municipal wastewater via DMF, it increased to 0.25 kWh per 1 m³ of the raw wastewater. Additionally, it should be pointed out that the wastewater examined in this study can be classified as “low strength”: the concentration of organic matter was lower than that in typical wastewater (around 430 mg/L of COD) (Metcalf and Eddy, 2003). Therefore, when DMF is applied to typical, stronger wastewater, a larger amount of energy can probably be generated. When a similar recovery of organic matter (~75%) and a doubled concentration of COD in the raw wastewater are assumed, potential energy production by DMF from 1 m³ of wastewater can reach 0.5 kWh. On the other hand, full-scale DMF is likely to be operated with energy consumption of <0.5 kWh/m³. MBRs share many aspects with the membrane process of DMF. It has recently been reported that full-scale MBRs can be operated with energy consumption of <0.4 kWh/m³ (Viswanath et al., 2013). DMF can be operated with much less energy than MBRs because it is not necessary to provide intensive aeration for membrane cleaning and oxygen supply for biomass. If membrane fouling is still not so severe, net energy balance in the wastewater treatment system with DMF may therefore be positive. This is opposite to the current practice that consumes a huge amount of energy to degrade organic matter.

3.4.2. Required space and sludge handling: comparison with the existing plant

Feasibility of the proposed DMF in terms of space requirement and sludge handling is discussed in this section. For this purpose, available information on the wastewater treatment plant from which the raw wastewater was collected is used.

Total hydraulic retention time (HRT) in DMF was 80 min (concentration factor of 21) or 110 min (concentration factor of 50). Hydraulic retention time in DMF examined in this study is much shorter than the HRT of the primary sedimentation tank of the wastewater treatment plant (3.5 h). Therefore, the space currently used for primary sedimentation is enough to install the DMF system, and the space currently used for aeration and secondary sedimentation can be used for further purification of the effluent from

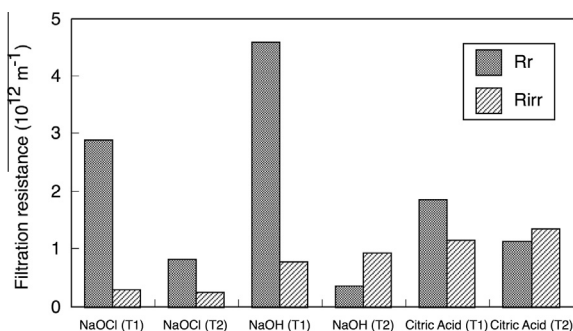


Fig. 5. Distribution of reversible (R_r) and irreversible (R_{irr}) filtration resistances in the fouled membranes (concentration factor: 50).

DMF. Quality of the effluent from DMF is not sufficiently high for discharge into natural water bodies (see Table 1). Ammonium nitrogen cannot be removed by DMF at all. The space required for treatment of the effluent from DMF is, however, should be very compact because 70–80% of COD is already removed by DMF. Also, recovery of nitrogen and phosphorus in the DMF effluent might become feasible by using the newly available space created by installation of DMF.

The volume of the product that is potentially used for energy generation was 2% of the raw wastewater treated in the case of a concentration factor of 50. As stated above, this volume can be further reduced by optimisation of the system. The Soseigawa wastewater treatment plant produces 2976 m³ of primary sludge and 1953 m³ of excess sludge daily, while treating 124,000 m³ of wastewater daily. The sum of primary and excess sludge corresponds to approximately 4% of the volume of wastewater treated. The volume of the product from DMF can be much smaller than the volume of sludge produced by the currently working wastewater treatment plant and is therefore manageable with the space used in the current wastewater treatment system.

4. Conclusions

In this study, DMF of municipal wastewater for recovery of organic matter was investigated. About 75% of organic matter in wastewater could be recovered by DMF, whereas membrane fouling in DMF could be effectively mitigated by CEB using NaOCl or citric acid. A comparison was also made between DMF and current wastewater treatment, suggesting that DMF can be installed and performed within the space used for currently working systems. Therefore, in retrofitting activated sludge systems, DMF is an attractive option as it is sufficiently compact and can produce a lot of energy.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.biortech.2013.09.111>.

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