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Combined FO and RO system for the recovery of energy from wastewater and the desalination of seawater

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ABSTRACT

Organic matter (OM) found in wastewater represents a potential source of energy through anaerobic digestion which produces methane. However, for efficient anaerobic digestion, the OM found in raw wastewater must be concentrated to levels greater than 1,500 mg/L COD. Indeed, a COD concentration greater than 1,500–2,000 mg/L would be required for the process to generate its own heat and produce methane in a more efficient way without an external heat. In this study, the feasibility of recovering OM from wastewater with a forward osmosis (FO) process using seawater or seawater brine as a draw solution is presented. We report on the performance of different brine concentrations as draw solutions for the FO process during wastewater concentration and explore what their usage implies for the energy balance (energy recovered from OM minus the energy spent on FO and on recirculation). Two scenarios were evaluated. In the first scenario, we consider the configuration where reverse osmosis (RO) membranes are operated at different recovery rates to produce potable water and brine is used as a draw solution for FO. In the second scenario, seawater is used as a draw solution and the diluted draw solution (during FO operation), is fed to the RO membrane to produce potable water. In this study, we evaluate the theoretical energy consumption and energy recovery from concentrated sludge in each configuration.

Keywords: Energy; Desalination; Organic matter; Recovery; Wastewater

1. Introduction

Water, energy and food are basic components of life, and the demand for water, energy and fertilizers for food production to sustain humans on Earth is increasing. However, securing these resources at an affordable cost and with low environmental impacts is becoming challenging. Therefore, recycling and resource recovery are crucial points of concern. Although the intricate linkages between water, energy and fertilizers are widely recognized, they still tend to be managed independently of each other. Wastewater offers the opportunity to take a more integrated approach in the management of these resources. Wastewater is rich in water and nutrients (phosphate, nitrogen, potassium) as well as organic matter which can serve as an energy source [1]. However, a closer look at water treatment technologies reveals that the technology most commonly used today, known as activated sludge (AS) process, is a dissipative one. It requires a huge

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amount of energy to degrade the organic matter and nutrients to inert forms such as CO_2 and N_2. Researchers reported an energy consumption of 0.15–0.25 kWh/m^3 of for AS [2,3]. Yet, the organic matter contained in municipal wastewater has the potential to be utilized as a new important energy resource. Salter [4] claims that the energy potential in wastewater chemicals could be up to 10 times the energy required for its treatment. McCarty et al. [5] found that the complete conversion of 500 mg COD/L produced 1.93 kWh/m^3. The energy consumption for its treatment using an aerated membrane bioreactor was in the range of 0.5–0.7 kWh/m^3 [6]. Mizuta and Shimada [7] reported that consumption by the AS system to treat the same concentration of water was between 0.3 and 1.9 kWh/m^3. It should be noted that typical COD concentration in municipal wastewater ranges from 250 to 800 mg/L, underlining the energy potential of wastewater.

Nowadays, there is a paradigm shift toward resource recovery (nutrients, energy and water). Anaerobic digestion is one of the simplest ways to recover the energy in the form of methane. However, due to the low concentration of organic matter, a significant input of energy is required in the form of heating. It is difficult to apply anaerobic processes to wastewater with concentrations of <1,500–2,000 mg/L [1]. Therefore, concentration of organic matter in excess of 1,500 mg/L would be necessary for energy recovery through anaerobic digesters to be feasible without an external energy input. One promising possible way to pre-concentrate organic matter is with anaerobic membrane bioreactors using micro- or ultra-filters [8,9]. Lateef et al. [9] reported a recovery of 75% of the organic matter found in wastewater using an anaerobic membrane bioreactor. However, fouling was a major drawback of this method. A more energy-efficient method of concentrating organic matter is required, and forward osmosis (FO) emerges as a promising option. FO is an osmotic process with a semipermeable membrane which is driven by the differential in chemical potential between two solutions, thereby reducing the need for external power to operate the system. Furthermore, FO has the advantage of low fouling tendency. FO membranes are of concern in different applications and these include but not limited to desalination, food processing, wastewater treatment, water contaminated with nuclear waste, urine concentration [10–13]. Our ongoing investigation on the feasibility of increasing urine concentration using FO membranes showed FO to be a promising technology for resource recovery due to its high selectivity, simplicity of operation and reduced fouling. Forward osmosis is proposed in this study as a process to concentrate wastewater.

However, the efficiency of the FO process is highly dependent on the choice of draw solution which can adversely affect its cost effectiveness. On the other hand, seawater desalination is commonly used in water-scarce countries to produce fresh water. Due to significant technical advances and low energy consumption, reverse osmosis (RO) has become predominant in the thermal processes. However, it remains an energy-intensive process with power consumption ranging from 1.5 to 3 kWh/m^3 of fresh water. Therefore, the combination of FO and RO processes for energy recovery and water production could be an attractive option. The brine solution from the RO process could serve as a draw solution. It is obvious that an FO process with a more concentrated brine draw solution would achieve a higher flux and better organic matter concentration. However, the corresponding process using RO to make the draw solution from seawater would be more costly as it would require more energy. For practical applications, we need to strike a balance between the quality of water recovered and cost incurred in the draw recovery process.

To our knowledge, very few studies explore the feasibility of such a combination from an energy point of view. The objective of this study is to investigate the feasibility of this approach. The study will focus on the energy consumption and energy recovery in order to propose an optimal system. An experimental study will be carried out to assess levels of OM concentration using different draw solution concentrations and to estimate the theoretical methane yield. Then, scenarios with different combinations will be considered to estimate their energy consumption.

In this study, our aim was to assess the feasibility of a system combining both FO and RO processes for energy recovery from wastewater and for seawater desalination. The study will focus on the energy consumption and energy recovery in order to propose an optimal system.

2. Approaches and methods

2.1. Experiment: organic matter concentration

Lab-scale FO experiments were carried out using real wastewater as feed solution and NaCL solution as draw solution representative of different concentrations of seawater or seawater brine expelled from the RO process. Experimental layout, shown in Fig. 1, consisted of an FO cell, a draw solution tank and a feed solution tank. FO cells consist of a sinusoidal channel separated by a semipermeable cellulose triacetate membrane purchased from Fluid Technology Solutions, USA. The area of the cross section of the channel was 0.2 cm^2 and the effective filtration area

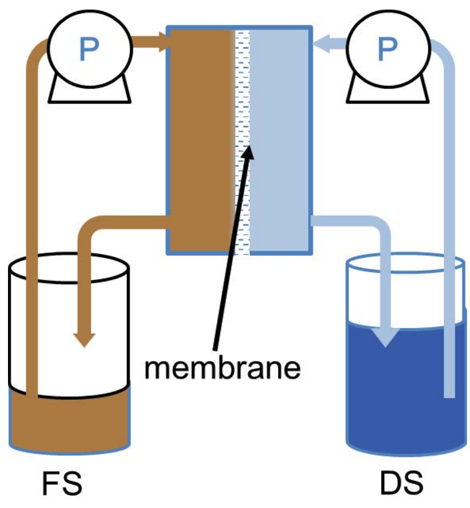

Fig. 1. Experimental layout.

was 98.27 cm^2. Draw and feed solution (1L of each) were recirculated in co-current mode using peristaltic pumps. Wastewater from the inlet of a primary sedimentation tank was used as a feed solution, while NaCl solutions with 0.5, 1.0 and 2.0 M were used as draw solutions. As sodium chloride ions provide more than 97% of the osmotic pressure of seawater, the FO draw solution was prepared using NaCl only for the sake of simplicity. It is worth mentioning that seawater has an average osmotic pressure of 2.5 MPa which is equivalent to 0.5 M NaCl solution. The 1 and 2 M NaCL solutions represent the brines at 50% and 75% recovery rates, respectively. A flow rate of 14 (L/m^2/h) L was used. Experimental conditions are summarized in Table 1. The concentration of OM in the feed solution was measured by means of a spectrophotometer (DR. 2800 Hach Company, Colorado, USA). The change in weight of the draw solution was measured using an electrical balance OHAUS (OHAUS Corporation, Tokyo, Japan) connected to a computer installed with data collection software WINCT (A&D Company Limited, Tokyo, Japan). The concentration factor (CF) is calculated by the following equation:

$$\text{CF} = \frac{V_{Ft}}{V_{Fi}} \tag{1}$$

where V_{Fi} is the volume of feed at time zero; V_{Ft} is the volume of feed at time *t*.

Table 1
Experimental conditions

Feed solution	1 L of wastewater (300 mg COD/L)
Draw solution	1 L of NaCl solution
	0.5 M: seawater
	1.0 M: 50% water recovery rate with RO
	2.0 M: 75% water recovery rate with RO
Membrane	Cellulose triacetate
Cross flow velocity	3.9×10^{-4} (m/s)
Flow mode	Co-current

2.2. Study scenarios

Two different scenarios were evaluated in this study as shown in Figs. 2a and b. In the first scenario, seawater is fed to the RO process. Then, the brine expelled from RO is used as the draw solution for the FO process. The brine concentration is closely linked to the recovery rate of the RO unit. Using an NaCl solution of 0.5 M (seawater equivalent) will lead to draw solutions of 1 and 2 M at recovery rates of 50% and 75%, respectively. In the second scenario, seawater is used as the draw solution for FO and the diluted draw solution is run through RO to re-concentrate it to a level comparable with seawater and therefore produce fresh water out of it.

2.3. Energy consumption of the combined system of FO and RO

Estimation of the energy requirements of this proposed system depends on the real configuration of the proposed system. However, for the sake of simplicity, we can assume that the energy consumption of the system includes the energy consumption for the operation of the FO and RO units. This includes the energy required for water circulation in the FO unit as well as the energy used by the RO unit to desalinate seawater as well as the energy spent to control fouling. For the sake of simplicity the energy consumed to control fouling is not considered in this paper. It is important to remember that FO has a tendency for low fouling.

Total energy consumption, E_t (kJ/m^3), is calculated by:

$$E_t = E_{\text{RO}} + E_{\text{recirc}} + E_C \tag{2}$$

where E_t (kJ/m^3) is the total energy required for the operation of the proposed system; E_{RO} (kJ/m^3) is the energy spent to produce the concentrated draw solution from seawater, which is the same as the minimum thermodynamic energy required to separate water and salts $E_{\text{minimum thermodynamic}}$ (kJ/m^3); E_{recir} (kJ/m^3) is the energy used for recirculation of water in FO; E_c (kJ/m^3) is the energy used to clean the FO membrane.

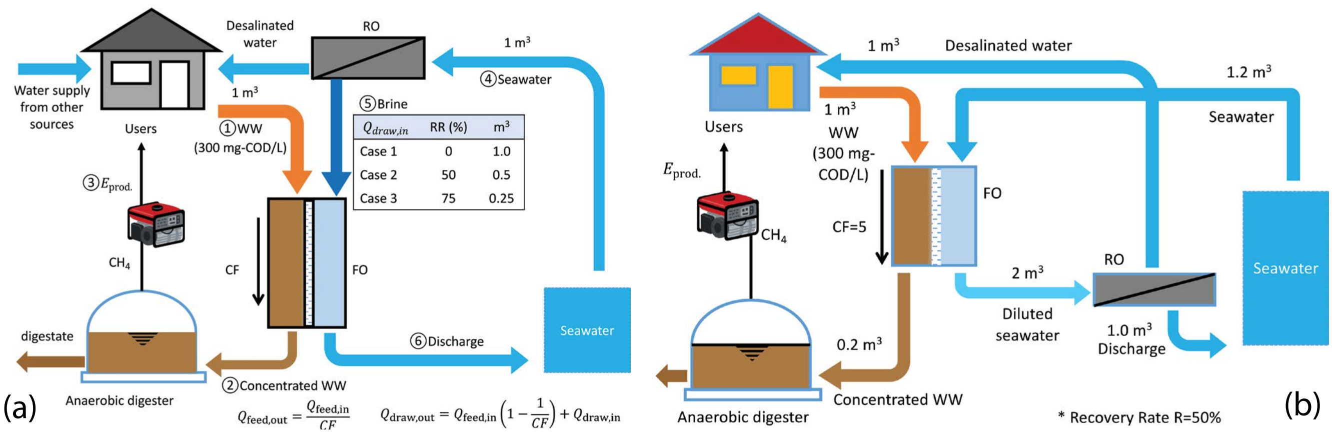

Fig. 2. Two different scenarios considered in this study: (a) FO following RO and (b) RO following FO.

It should be noticed that energy required for fouling and scaling control (cleaning, back washing, chemical washing, etc.) in FO and RO membranes was not considered in this study. It is also important to note that FO is expected to have low fouling potential.

2.4. Minimum energy required for desalination

Energy for the RO system is needed to separate salt from water, and the products are the permeate water and the brine (concentrated solution). The minimum thermodynamic energy required to separate water from seawater depends on the recovery rate as shown in Eq. (1). The minimum thermodynamic energy is calculated for both scenario 1 using an initial NaCl solution of 0.5 M (seawater equivalent) and for scenario 2 with NaCl solution with a concentration of 0.28 M (1.8 times diluted brine).

Energy for RO system is needed to separate salts from water, and the products will be the permeate water and the brine (concentrated solution). Researches exemplified by the works of Spiegler and El-Sayed [14], Feinberg et al. [15], Cengel and Boles [16] and Abhishek et al. [17], among others addressed the minimum energy required for desalination. Indeed, from the thermodynamics theory, the minimum work required per mole is independent of the process itself and it is equal and opposite in sign to the Gibbs free energy for mixtures [18,19].

$$W = -\Delta G \tag{3}$$

A study by Spiegler and El-Sayed [14] indicate that the minimum work required for the separation of two components from a mixture, salt and water in this case, can be interpreted in a way suiting the desalination method. It was also pointed out in the study that the minimum work required for separation of an infinitesimal amount of water from salt solution using RO can be calculated using Van't Hoff's equation, written as follows:

$$W \cong \pi V \tag{4}$$

And the osmotic pressure π (bar) is estimated using the following equation:

$$\pi = iMRT \tag{5}$$

where M: molarity; R: 8.021 constant; T: temperature (K); V: volume of product water (m^3), i: Van't Hoff's factor.

Feinberg et al. [15] and Shrivastava et al. [17] mentioned that Eq. (4) could be integrated over the water recovery desired as follows:

$$E_{\text{RO}} = E_{\text{minim thermodynamic}} = \frac{1}{R}\int_0^R \pi dR \tag{6}$$

where E: minimum energy required (kJ/m^3); R: recovery rate (0%–100%); π: osmotic pressure of a solution (bar).

The minimum thermodynamic energy is calculated for both aforementioned scenarios. In the first scenario, feed water to RO unit is seawater with an equivalent NaCL concentration of 0.5 M. In the second scenario, the feed water to RO membrane is a diluted sea water of 0.5 M NaCL concentration. The dilution level will be obtained from experimental data.

2.5. Energy required for recirculation in FO unit

We consider the pumping arrangement shown in Fig. 3. FO needs energy to recirculate both feed and draw solutions. Water is pumped from a one reservoir to flow through the FO unit and then back to the same reservoir. The system is equipped with two identical pumps, used to circulate feed and draw solutions. We assume that the hydraulic circuits are identical too (comparable sizes and friction losses). Also for the sake of simplicity, we assume that the fluids have the same properties. The power requirement for one pump can be calculated using the following equation:

$$E_{\text{recir.}} = \frac{1}{3.6\times 10^6}\times\frac{Q\rho g H}{\eta_\rho \eta_m} \tag{7}$$

where $E_{\text{recir,}}$ is the energy consumption; Q (m^3/d) is flow rate, ρ (kg/m^3) is the density of water, g (m/s^2) is the gravity acceleration, η_p and η_m are the pump and motor efficiencies, respectively, where H is the differential head; t is the operation time (h).

The differential head (H) is the sum of the static head (H_S) and dynamic head (H_D). The static head H_S is the difference in elevation between the surface of the reservoir and the highest point of discharge. Again we assume here that both circuits have similar head. The dynamic head is a compensation of head losses due to local and linear friction within the system. The head loss due to friction is calculated using the Darcy–Weisbach equation.

$$H_D = \frac{KV^2}{2g} \tag{8}$$

where K is the loss coefficient; v is water velocity (m/s) and g is the gravity acceleration (m/s^2).

The loss coefficient is the sum of linear losses (K_L) and singular losses (K_S). Singular losses are those related to the fittings assembled on the system and their coefficients are obtained from standard tables. Linear losses coefficient is estimated using the following equation:

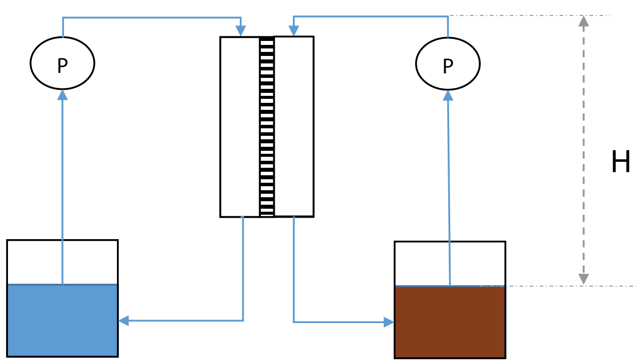

Fig. 3. Considered pumping arrangement for circulation energy requirement calculation.

$$K_L = \frac{fL}{D} \tag{9}$$

where f is the friction coefficient obtained from Eq. (10).

$$f = \frac{0.25}{\left[\log\left\{\frac{k}{3.7D} + \frac{5.74}{\mathrm{Re}^{0.9}}\right\}\right]^2} \tag{10}$$

where Re is Reynolds number and k is the pipe roughness factor obtained from standard tables depending on pipe material and its internal coating.

It is important to mention that these calculations are cases dependent and therefore cannot be generalized. Therefore, calculations were performed for case studies to get a rough estimation of energy use for recirculation.

2.6. Energy recovery by the combined FO and RO system

The energy production from OM by anaerobic digestion reactor, E_{prod} (kJ/m^3), can be calculated as follows:

$$E_{\text{prod.}} = u_{\text{CH}_4} \times k \times C_{\text{OM}} \tag{11}$$

where u_{CH_4} (kWh/m^3) is the energy density, k (m^3 CH_4/mg COD) is the production ratio of methane per milligram of organic matter and C_{OM} (mg COD/m^3) is the concentration of OM in concentrated wastewater. The constant values are as follows:

$$u_{\text{CH}_4} = 10$$
$$k = 0.34$$

3. Results

3.1. FO experiment for organic matter concentration:

Time courses of organic matter concentration in feed water and concentration factors are shown in Fig. 4. Three different concentrations of draw solution were examined, namely 0.5, 1 and 2 M of NaCl solution. These solutions produce an osmotic pressure of 2.5, 5 and 10 MPa, respectively. In the three cases, a COD concentration of higher than 1,500 mg/L was achieved, corresponding to a fivefold increase in concentration. In the case of the highest concentration (2 M), a fivefold increase in concentration was achieved within about 9 h. However, it is worth mentioning that concentration factor increases exponentially, and an additional hour of operation produced a ninefold increase in concentration, bringing the COD concentration to more than 2,500 mg/L. This level of concentration permits effective anaerobic digestion without an additional heating source. Increased concentration of the draw solution produced a higher rate of concentration. However, an energy balance evaluation is required to assess which configuration is most efficient.

3.2. Energy balance in FO unit

Fig. 5 (red dots) shows the energy harvested from organic matter in the form of methane by an anaerobic digester of

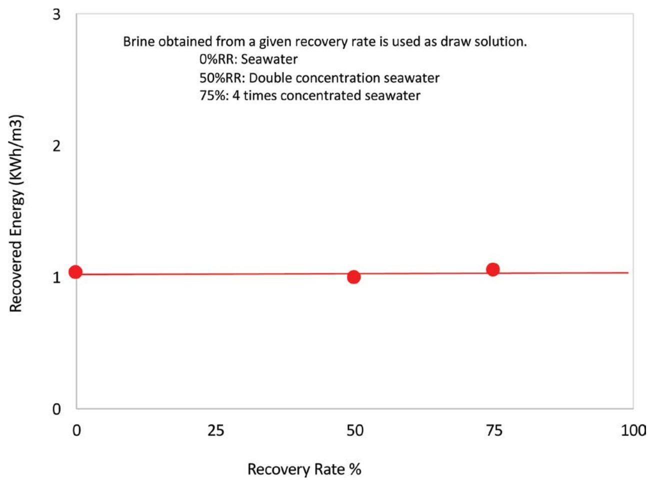

Fig. 5. Recovered energy.

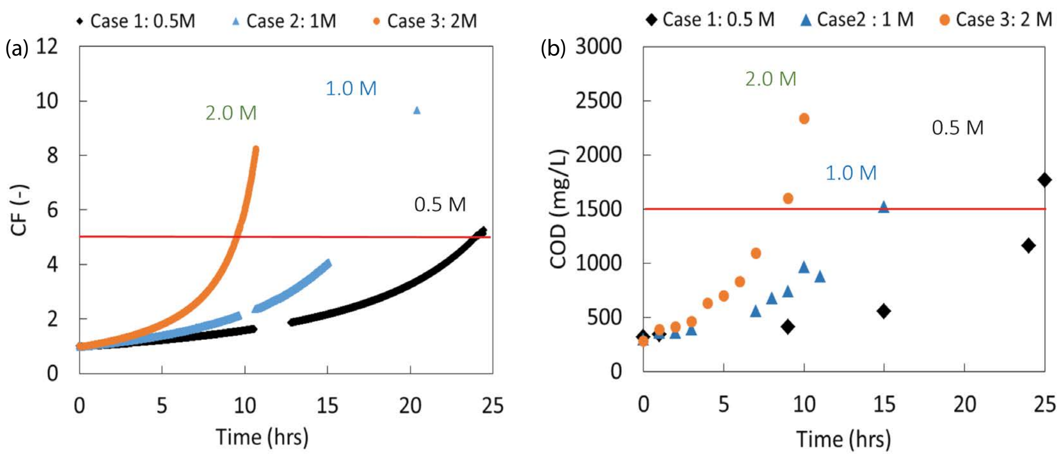

Fig. 4. Results of the FO process for wastewater concentration using different concentrations for the draw solution. (a) Concentration factor, (b) COD concentration levels.

the concentrated wastewater. Since there is almost no loss of organic matter by degradation or by diffusion to the draw solution side during the FO concentration phase, almost 100% of the organic matter is recovered. Therefore, it could be said that the energy recovered is independent of the draw solution concentration or indeed independent of the recovery rate. Again, we note that the recovery rate of the RO unit determines the level of concentration of the draw solution. The energy recovered from wastewater containing 300 mg/L initially in all cases of the three concentration levels is about 1 kWh/m^3, which is almost equivalent to 100% recovery. As was mentioned earlier, McCarty et al. [5] found that the full conversion of 500 mg COD/L would produce 1.93 kWh/m^3. This highly concentrated solution has the advantage of not requiring extra heating, making the methane recovery more efficient.

Depending on the draw solution used, the FO unit is operated for specific periods of time to achieve a level of concentration. For instance, using 0.5 M NaCl solution, it took 24 h to achieve a fivefold increase in concentration, while it took less than 10 h to achieve a ninefold increase in concentration using the 2 M NaCl solution. The energy required for recirculation over these periods was estimated and is shown in Fig. 6. It was found that recirculation in general consumed a very small fraction of the total energy (<0.015 kWh/m^3).

3.3. RO energy consumption

Energy consumption by the RO process is calculated for two different scenarios. In the first scenario, seawater is used as the feed. For sake of simplicity, we assume NaCl concentration for seawater of 0.5 M. The minimum thermodynamic energy required to produce fresh water is calculated according to the recovery rate. A 50% recovery rate produces a brine solution of 1 M NaCl concentration and a 75% recovery rate corresponds to production of a brine solution of 2 M NaCl.

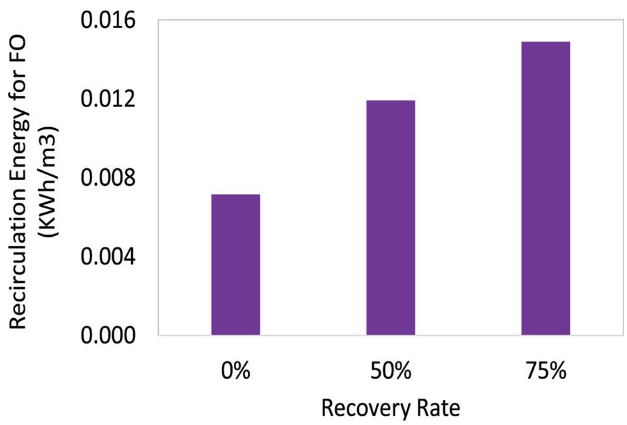

Fig. 6. Recirculation energy.

In the second scenario, seawater is first fed to the FO unit, and then, after a fivefold increase in concentration of the wastewater, the resulting draw is 1.8 times more diluted than the original draw solution. This diluted seawater with a molarity of 0.28 was fed to RO to produce fresh water and produced a brine with a concentration equivalent to sea water for safe discharge.

Fig. 7 illustrates the overall energy of the system, energy consumption in the two scenarios and the theoretical energy yield from anaerobic digestion of the organic matter found in the concentrated wastewater. In scenario 1, larger amount of energy is consumed. This is explained by the fact that the energy required to separate water from a salt solution increases with salt concentration. It is worth reminding that in scenario 1 seawater was used, while in scenario 2 diluted seawater was used. In contrast, the consumption was much less in scenario 2, with a positive net energy balance of 0.81 kWh/m^3 being achieved. Diluting seawater first using the FO system helps the RO system to reduce the demand for energy.

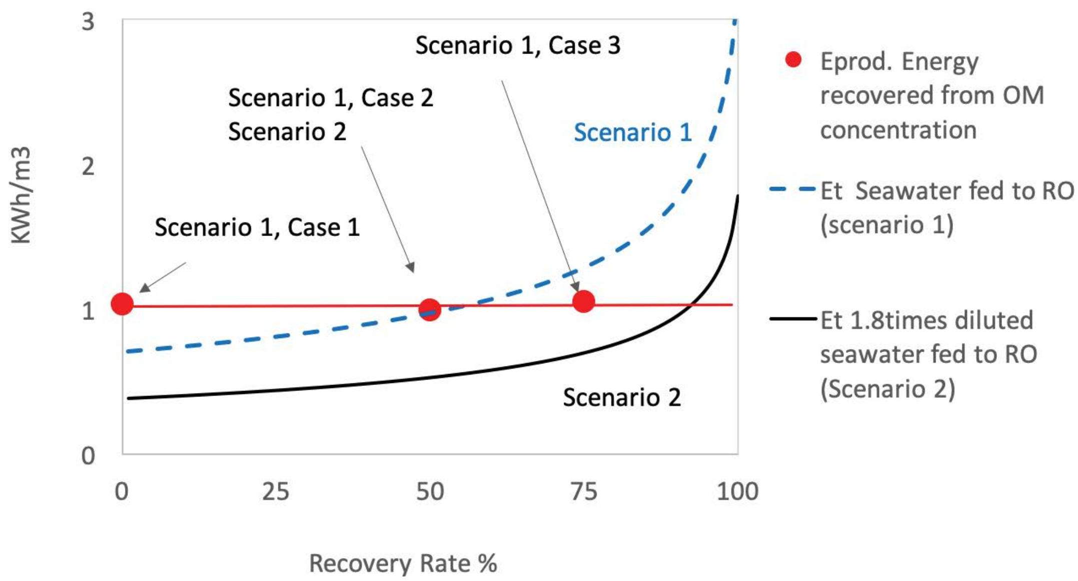

Fig. 7. Energy balance of the different scenarios.

4. Conclusions

This study demonstrated the feasibility of concentrating wastewater by FO using seawater and brine from RO desalination plants as a draw solution. The concentration of the organic matter in the feed solution was increased by a factor of 5–10 times, far exceeding the 1,500 mg/L threshold, the minimum limit for anaerobic digestion to be efficient by eliminating the need for extra heating. Using more concentrated brine produced a higher concentration of the organic matter at a faster rate, thereby reducing the operating time and, in turn, the energy required for recirculation of the feed and draw solutions. It was also found that little or no organic matter is lost during the concentration process and nearly all organic matter was recovered regardless of operation time. The largest portion of energy consumed was for brine production and this was highly dependent on the feed solution of RO and the recovery rate. Lower energy consumption was achieved using diluted seawater rather than standard seawater as a feed solution. These findings explain why scenario 2 produced a more favorable outcome than scenario 1.

Acknowledgments

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