

Forward osmosis treatment of effluents from dairy and automobile industry – results from short-term experiments to show general applicability

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ABSTRACT

Forward osmosis (FO) is a potential membrane technology to treat wastewater energy efficiently with low fouling. In laboratory-scale experiments, six effluents from a dairy and an automobile production plant were tested to find out if FO is an applicable treatment technology. Permeate flux and reverse salt flux were determined in nine test series with three subsequent 5 h experiments each. In between, the membrane was cleaned with deionized water. Membrane performance tests before each experiment were used to monitor membrane performance and fouling. Samples were analysed and the T/M-value was introduced to indicate which substances caused fouling. Dairy cheese brine was a suitable DS. Here, permeate fluxes were 21.0 and 15.1 L/(m²·h). Automobile cooling tower water and wastewater from cathodic dip painting were also used as DS. However, permeate fluxes were below 1.1 L/(m²·h). The tested FS, reverse osmosis concentrate from dairy wastewater treatment, rinsing water and wastewater from automobile cathodic dip painting, as well as wastewater from automobile paint shop pre-treatment, showed good performance regarding the permeate flux of between 7.9 and 19.4 L/(m²·h). Membrane performance test showed that some of the effluents lead to permeate flux reduction due to fouling. Different cleaning-in-place methods were examined. Eventually, permeate flux was restored.

Key words | automobile industry, dairy, forward osmosis, industrial wastewater, membrane technology

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INTRODUCTION

In 2015, the United Nations (UN) defined 17 sustainable development goals (SDGs) (United Nations 2015). One of them is the 'availability and sustainable management of water and sanitation for all'. This goal, but also others, are directly linked to a sufficient water supply (Ait-Kadi 2016). Industry is consuming 19% of worldwide freshwater, making it the second largest consumer behind agriculture (70%) (WWAP 2017). In order to achieve all of the defined SDG, an efficient water usage in industrial production processes is therefore essential. Nowadays, modern treatment technologies are applied to clean industrial wastewater so

that it can be recycled. That way, industrial water demand as well as wastewater amount is reduced. However, wastewater treatment consumes a lot of energy (McGinnis & Elimelech 2008). Thus, to obtain sustainability, energy-efficient wastewater treatment technologies need to be promoted.

Membranes are frequently used treatment processes for industrial wastewaters. Ultra-, micro-, and nanofiltration as well as reverse osmosis (RO) are state of the art. The driving force of these conventional processes is a transmembrane pressure difference, which is technically generated by pumping, resulting in a high energy demand. This is necessary to overcome the flow and membrane resistances as well as the osmotic pressure increasing with high concentrations of dissolved water constituents. Another membrane process for water

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treatment is forward osmosis (FO): this uses the osmotic pressure directly as a natural driving force to overcome flow and membrane resistances. Water molecules pass through the membrane from a feed solution (FS) with low osmotic pressure into a draw solution (DS) with high osmotic pressure (Cath *et al.* 2006). Due to the low demand of external energy, FO offers potential for energy-efficient water treatment (Mazlan *et al.* 2016). Disadvantageous may be the fact that a second treatment step is necessary to obtain 'pure' water out of the DS (Luo *et al.* 2014; Chekli *et al.* 2016). Another negative effect occurring during FO treatment is the so-called reverse salt flux. This term describes that substances from the DS diffuse into the FS through the membrane, possibly changing FS composition (Phillip *et al.* 2010). In pressure driven membrane processes, reverse salt flux is less severe due to the high physical operating pressure. Still, FO is a promising approach for further concentration of aqueous product and sewage streams, for example in industries. FO might even be applicable for waters that are unsuitable for conventional membrane processes due to a high fouling potential (Zhao *et al.* 2012).

FO has already been used successfully in various applications. One of them is seawater desalination to produce drinking water (Modern Water 2017). Furthermore, FO is applied for emergency water supply in so-called hydration bags, where a sugar-based DS and a membrane is used to clean contaminated water. Here, the result is a sweet, mineral-containing drink (Loo *et al.* 2012). Another application field is the treatment of wastewater from oil and gas production as well as from mining (Coday *et al.* 2016; Thiruvengkatachari *et al.* 2016; Zhao *et al.* 2017). Even agricultural use of FO is examined: concentrated fertilizer solutions are used as DS, diluted and then used for irrigation. This combined process of irrigation and fertilization is called fertigation (Chekli *et al.* 2017; Kim *et al.* 2017). In biological wastewater treatment, the separation of activated sludge

and cleaned wastewater may also be done by the FO process in a so-called osmotic membrane bioreactor, though reverse salt flux and its influence on microbial activity seems to be a major issue here (Wang *et al.* 2016). As can be seen, different types of water are subjects for FO application. However, so far there are few findings regarding the FO treatment of industrial effluents or wastewater. For this reason, laboratory tests were carried out to examine the FO application for the treatment of effluents from the dairy and automobile industry. In this paper, the results of nine test series are presented.

MATERIAL AND METHODS

Experimental set-up

A closed-loop laboratory-scale FO system was used for the experiments (Figure 1). The included flat-sheet test cell had an effective membrane area of 48 cm² with symmetric channel dimensions of 1,200 mm in length, 40 mm in width, and 0.86 mm in depth on both sides of the membrane. The FS as well as DS flow channel contained a 34 mm propylene spacer from Hydranautics – A Nitto Group Company (USA). FS and DS were pumped through the cell in counter-current mode throughout all experiments shown here. Pumps were from Micropump Inc. (USA) and GATHER Industries GmbH (Germany). The flow rate was automatically measured and recorded so that the pumping rate could be manually adjusted to the desired flow rate.

The FS and DS tanks were each placed on a digital scale (Sartorius AG and KERN & SOHN GmbH, Germany) and continuously stirred using a magnetic stirrer (Heidolph Instruments GmbH and IKA[®]-Werke GmbH & CO. KG, Germany). FS weight was measured continuously but only recorded manually if needed. DS weight was

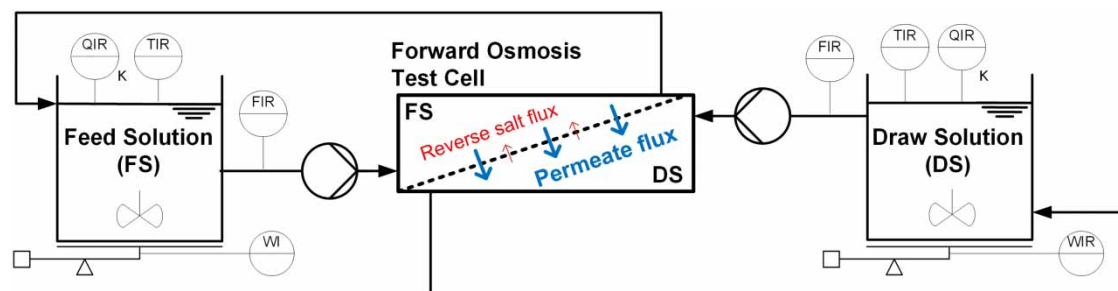


Figure 1 | Laboratory-scale FO system with indication (I) and registration (R) of flow rate (F), quality parameter (Q) here electrical conductivity (κ), temperature (T), and weight (W).

measured continuously and recorded constantly using a data-logger (Delphin Technology AG, Germany). The recorded DS weight change was used to determine permeate flux. Meters in the FS and DS tank from Hach Lange GmbH (Germany) recorded the conductivity (κ) and temperature (T), which were used to calculate the reverse salt flux.

Membranes

Different FO membranes were used in the laboratory set-up. Experiments with dairy effluents were conducted using a HTI OsMemTM TFC-ES membrane from Hydration Technology Innovations, LLC (HTI, USA), whereas experiments with automobile effluents were conducted with the CSM FO membrane from Toray Chemical Korea Inc. (South Korea). The indicated standard permeate flux was 18 L/(m²·h) for the HTI membrane and 30 ± 5 L/(m²·h) for the Toray membrane. The HTI membrane was stored in dry condition because the manufacturer had conserved the membrane with vegetable-based glycerine. The Toray membrane was stored in 1% sodium bisulphite solution. Before the experiments, the membranes were cut to size and put in deionized water for at least 30 minutes. A new Toray membrane was used for each of the test series regarding automobile effluents. In the dairy experiments, one HTI membrane was used for all test series.

Experiments with industrial effluents as feed and draw solutions

As a first step, data from a dairy and an automobile production site was evaluated. Possible FS and DS were determined. Criteria considered were above all the electrical conductivity and the desired dilution or further concentration of the effluent. Regarding the dairy, wastewater treatment RO concentrate and cheese brine were chosen for FO experiments. Four effluents were chosen from the automobile production site: they are cathodic dip painting rinsing water, cathodic dip painting wastewater, paint shop pre-treatment wastewater, and cooling tower circulation water.

The osmolality of the effluents was measured with a freezing-point microosmometer (Hermann Roebling Messtechnik, Germany). One sample of each effluent was used for three osmolality measurements. Afterward, the osmotic pressure was calculated applying Equation (1) given in (Grattoni *et al.* 2008), where π is the osmotic pressure, c_{osm} the average osmolality, R the universal gas constant,

and T the temperature.

$$\pi = c_{\text{osm}} \cdot R \cdot T \quad (1)$$

Furthermore, all chosen effluents were analysed including the following parameters: pH, conductivity (κ), chemical oxygen demand (COD), total organic carbon (TOC), dissolved organic carbon (DOC), turbidity, total suspended solids (TSS), acid-base capacity ($K_{\text{S4,3}}$; $K_{\text{B8,2}}$), aluminium, ammonium, lead, cadmium, calcium, chloride, iron, potassium, copper, magnesium, molybdenum, sodium, nickel, nitrate, nitrite, phosphate, silicon, and sulphate. From dairy, three samples of each effluent were analysed; from the automobile industry, one sample of each effluent was analysed. Extracted information about the effluent composition and osmotic pressure are provided in Table 1.

FO experiments with industrial effluents were conducted in ALFS mode for 5 hours with an initial FS and DS volume of 1 L. The flow velocity on both sides of the membrane was 20 cm/s. First, the effluents were used as FS or DS and combined with 1 mol/L NaCl (DS) or deionized water (FS). Additionally, two combinations with an industrial effluent as FS and another industrial effluent as DS were tested. An overview of all test series can be found in Table 2. Between the experiments of one test series, the membrane was kept in the test cell and rinsed with deionized water being pumped through the FS and DS feed channel with a velocity of 20 cm/s.

During the experiments, FS weight, DS weight, FS conductivity, and DS conductivity were recorded either

Table 1 | Composition and osmotic pressure of industrial effluents

Effluent	π (bar)	κ (mS/cm)	pH (-)	COD (mg/L)	TSS (mg/L)
<i>Automobile effluents (one sample)</i>					
Cathodic dip painting rinsing water	0.8	0.15	4.4	4,190	588
Cathodic dip painting wastewater	2.1	4.53	2.1	890	0
Paint shop pre-treatment wastewater	1.0	1.01	3.1	91.1	18
Cooling tower circulation water	1.1	1.28	10.1	27.3	61
<i>Dairy effluents (average value of three samples)</i>					
Wastewater treatment RO concentrate	6.9	11.9	7.4	78.6	0
Cheese brine	158	214	4.9	11,913	2,491

Table 2 | Conducted test series

	Feed solution (FS)	Draw solution (DS)	$\Delta\pi$ (bar)
Automobile effluents			
[A1]	Cathodic dip painting rinsing water	1 mol/L NaCl	44.8
[A2]	Deionized water	Cooling tower circulation water	1.1
[A3]	Paint shop pre-treatment wastewater	1 mol/L NaCl	44.5
[A4]	Deionized water	Cathodic dip painting wastewater	2.1
[A6]	Cathodic dip painting wastewater	1 mol/L NaCl	43.5
[A7]	Paint shop pre-treatment wastewater	Cooling tower circulation water	0.05
Dairy effluents			
[D1]	Deionized water	Cheese brine	158
[D2]	Wastewater treatment RO concentrate	1 mol/L NaCl	36.6
[D3]	Wastewater treatment RO concentrate	Cheese brine	151

automatically via data-logger or manually. Moreover, the treated effluents after FO were analysed (only for automobile effluents to derive deposition processes, reverse salt flux concentration and composition). Based on these measurements, permeate flux J_W , reverse salt flux J_S , specific reverse salt flux J_S/J_W , and the ratio of theoretical concentration and analysed concentration (T/M-value) were determined.

Permeate flux was calculated with DS volume change ΔV_{DS} , membrane surface area A_M , and the corresponding time difference Δt according to Equation (2). DS volume change was calculated by dividing the recorded weight change by the DS density, which was assumed to be 1 kg/L because only water molecules are supposed to pass through the membrane, causing DS weight increase.

$$J_W = \frac{\Delta V_{DS}}{A_M \cdot \Delta t} \quad (2)$$

Reverse salt flux was calculated using Equation (3), where β_t and β_0 are the NaCl mass concentration in the beginning and at the end of the time interval, and V_t and V_0 the corresponding FS volumes. To obtain the FS volume, FS weight was divided by the density, which was

assumed to be 1 kg/L.

$$J_S = \frac{\beta_t \cdot V_t - \beta_0 \cdot V_0}{A_M \cdot \Delta t} \quad (3)$$

NaCl concentration for reverse salt flux calculation was derived from an empirically obtained correlation between conductivity and a virtual NaCl concentration. This correlation is given in Equation (4) with β being the virtual NaCl concentration in mg/L, and κ the electrical conductivity in $\mu\text{S}/\text{cm}$.

$$\beta = 5.703 \cdot 10^{-7} \cdot \kappa^2 + 4.915 \cdot 10^{-4} \cdot \kappa - 6 \cdot 10^{-4} \quad (4)$$

Membrane performance deterioration, cleaning and fouling

To monitor the membrane performance before and in between test runs, membrane performance tests were conducted. These tests lasted 120 minutes. Deionized water and 1 mol/L sodium chloride solution were used as FS and DS, respectively. The flow velocity in both flow channels was 20 cm/s. Initial FS and DS volume was 1 L. The membrane orientation was maintained in accordance with the previous and subsequent test run. In between experiments, the membrane remained in the test cell and cleaning was applied by rinsing with deionized water on both FS and DS side. First, 2 L of deionized water were pumped through the test cell as FS and DS, respectively. Afterwards, 1.5 L of deionized water were circulated on both FS and DS side for at least 15 hours. The flow velocity was 20 cm/s, the same as in the experiments. By comparing the membrane performance tests of one test series, it was possible to see if fouling occurred that was not easily removable by rinsing with deionized water.

In order to investigate substance behaviour during the FO process, the T/M-value was introduced and used for analysis interpretation. It is the ratio of theoretical concentration (T) and analysed (measured) concentration (M). The theoretical concentration of a substance is calculated by the analysed concentration in the untreated effluent and the dilution or concentration effect during the FO process. In this case, it is assumed that the substance remains in the effluent unchanged. Calculation was done as shown in Equation (5), where β_{start} and β_{end} are the concentration in the beginning and at the

end of the experiment, and m_{start} and m_{end} are the solution weight. The occurring density change was neglected.

$$T = \beta_{\text{end}} = \beta_{\text{start}} \cdot \frac{m_{\text{start}}}{m_{\text{end}}} \quad (5)$$

If T/M equals 1, the theoretical and the measured concentration are the same and the substance remains unchanged in the solution. If T/M is larger than 1, the measured concentration is smaller than the theoretical concentration and the substance gets lost during FO operation. If T/M is smaller than 1, the measured concentration is larger than the theoretical concentration. This means the substance increases during FO operation. One source for substance loss or increase may be a substance flow through the membrane. Another possibility is the accumulation or the detachment of substances on and off the membrane surface. By comparing the T/M-value of one substance for FS and DS, it is possible to find out if this substance causes fouling or reverse salt flux.

Within the regular FO experiments with industrial effluents, the membrane was only cleaned by rinsing

with deionized water as mentioned above (flow velocity 20 cm/s). After test series A7 however, in which the membrane performance decreased dramatically, different cleaning-in-place methods were applied one after the other with a membrane performance test in between each time (Table 3). All cleaning-in-place procedures were run in closed-loop mode. Since fouling was visible on the FS side only, cleaning procedures with chemicals were limited to this side of the membrane. Concentrated HCl and NaOH were used within the pH range that was given by the membrane manufacturer. Due to the limited availability of industrial effluents, cleaning experiments were only performed for one test series exemplarily.

RESULTS AND DISCUSSION

Permeate flux and reverse salt flux

FO laboratory-scale experiments were carried out with four effluents from an automobile production plant and two

Table 3 | Applied cleaning-in-place procedures after test series A7 (DI = deionized water)

FS	DS	Duration [h]	Flow velocity	Membrane performance test afterwards
DI	DI	15.1	$v = 20 \text{ cm/s}$	[A7]-P4
DI	DI	111.4	$v = 20 \text{ cm/s}$	[A7]-CP1
DI	DI	20.6	$v_{\text{(FS)}} = 30 \text{ cm/s}$, $v_{\text{(DS)}} = 20 \text{ cm/s}$	[A7]-CP2
DI	DI	20.9	$v_{\text{(FS)}} = 30 \text{ cm/s}$, $v_{\text{(DS)}} = 20 \text{ cm/s}$, opposite flow direction	[A7]-CP3
NaCl (1 mol/L)	DI	2.3	Osmotic backwash, $v = 20 \text{ cm/s}$	[A7]-CP4
DI	DI	90.1	$v = 20 \text{ cm/s}$	[A7]-CP5
HCl (0.001 mol/L)	-	1.3	$\text{pH} = 3.2$, $v_{\text{(FS)}} = 20 \text{ cm/s}$, $v_{\text{(DS)}} = 0 \text{ cm/s}$	-
DI	DI	20.5	$v = 20 \text{ cm/s}$	[A7]-CP6
HCl (0.01 mol/L)	-	1.2	$\text{pH} = 2.2$	-
DI	DI	17.4	$v = 20 \text{ cm/s}$	[A7]-CP7
NaOH (0.001 mol/L)	-	1.1	$\text{pH} = 11.1$, $v_{\text{(FS)}} = 20 \text{ cm/s}$, $v_{\text{(DS)}} = 0 \text{ cm/s}$	-
DI	DI	21.6	$v = 20 \text{ cm/s}$	[A7]-CP8
DI	DI	139.3	$v = 20 \text{ cm/s}$	[A7]-CP9
NaOH (0.001 mol/L)	-	2.4	$\text{pH} = 11.1$, $v_{\text{(FS)}} = 20 \text{ cm/s}$, $v_{\text{(DS)}} = 0 \text{ cm/s}$	-
DI	DI	16.4	$v = 20 \text{ cm/s}$	[A7]-CP10
NaOH (0.001 mol/L)	-	3.8	$\text{pH} = 11.1$, $v_{\text{(FS)}} = 20 \text{ cm/s}$, $v_{\text{(DS)}} = 0 \text{ cm/s}$	-
DI	DI	17.8	$v = 20 \text{ cm/s}$	[A7]-CP11
NaOH (0.001 mol/L)	-	2.5	$\text{pH} = 11.1$, $v_{\text{(FS)}} = 20 \text{ cm/s}$, $v_{\text{(DS)}} = 0 \text{ cm/s}$	-
DI	DI	65.8	$v = 20 \text{ cm/s}$	[A7]-CP12
DI	DI	19.0	$v = 20 \text{ cm/s}$	[A7]-CP13

effluents from a dairy. In this paper, the results of nine test series are presented. The effluents were either used as FS (with 1 mol/L NaCl as DS), as DS (with deionized water as FS) or in combination with one effluent as FS and another effluent as DS. If not mentioned otherwise, deionized water was used as FS and 1 mol/L NaCl was used as DS. Figure 2 shows the obtained permeate fluxes and the reverse salt fluxes that occurred. For each test series, the results from three subsequent experiments (T1, T2, T3) as well as the average value are shown.

Considering the automobile effluents (A1...A7), cathodic dip painting wastewater as FS (A6) reached the highest permeate flux, namely 19.4 L/(m²·h). Cathodic dip painting rinsing water (A1) and paint shop pre-treatment wastewater (A3) as FS produced moderate permeate fluxes of 12.1 and 7.5 L/(m²·h), respectively. Very low permeate fluxes were achieved when the DS was cooling tower circulation water (A2, A7) or cathodic dip painting wastewater (A4). Here, the permeate fluxes were between 0.1 and 0.3 L/(m²·h).

Regarding the dairy effluents (D1...D3), high permeate fluxes were obtained when cheese brine was used as the DS. Combined with deionized water as FS, the permeate flux was 21.0 L/(m²·h); with wastewater treatment RO concentrate as FS, the permeate flux was 15.1 L/(m²·h). A moderate permeate flux of 7.9 L/(m²·h) was achieved when wastewater treatment RO concentrate was the FS and combined with 1 mol/L NaCl as DS.

In general, the occurring reverse salt flux was high when the permeate flux was high, and low when the permeate flux was low. The highest reverse salt flux occurred when cathodic dip painting wastewater was used as DS (A4); that is, 21.3 g/(m²·h). Negative reverse salt fluxes took place when cathodic dip painting wastewater was the FS (A6). This means that substances from the FS passed through the

membrane into the DS. The reverse salt flux was calculated based on the conductivity change in the FS. However, there may also be other reasons for the conductivity change, e.g. remobilization of depositions from the membrane surface.

Membrane performance deterioration and fouling

Comparing the permeate fluxes of the three experiments for each test series, it is obvious that in some cases a decrease in permeate flux happened. This decrease shows that the industrial effluent had a negative impact on the membrane. This influence can also be seen in Figure 3(a), where the permeate flux for the performance tests is shown. Additionally, the ratio of permeate flux before the third experiment with industrial effluent (P3) and permeate flux before the first experiment (P1) is indicated. A high P3/P1-ratio means that the membrane performance did not deteriorate; a low P3/P1-ratio means that the membrane performance declined dramatically. Furthermore, the standard permeate flux given by the membrane manufacturer is visualized with a horizontal line in Figure 3(a).

During the dairy test series, only a small deterioration in membrane performance was noticeable although deposition on the membrane surface was visible. However, with some automobile effluents membrane performance decreased significantly. Standard permeate flux dropped to 39% with cathodic dip painting rinsing water as FS (A1), and even worse to 19 and 28% with paint shop pre-treatment wastewater as FS (A3, A7). Moderate influence was recorded when cathodic dip painting wastewater was used as DS (A4) and FS (A6). Here, standard permeate flux dropped to 60 and 57%, respectively. Cooling tower circulation water had only little effect on membrane performance (A2).

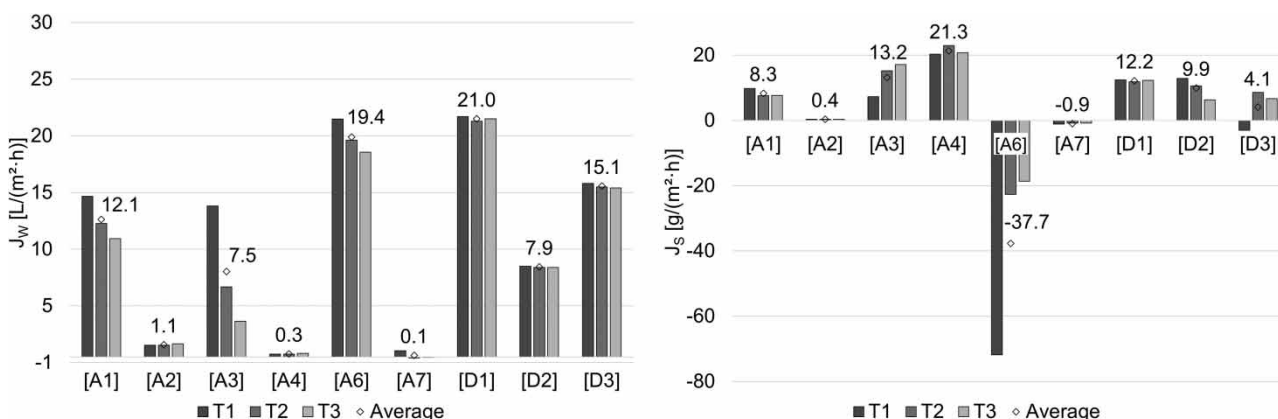


Figure 2 | Permeate flux J_w and reverse salt flux J_s obtained in the laboratory-scale FO experiments with industrial effluents.

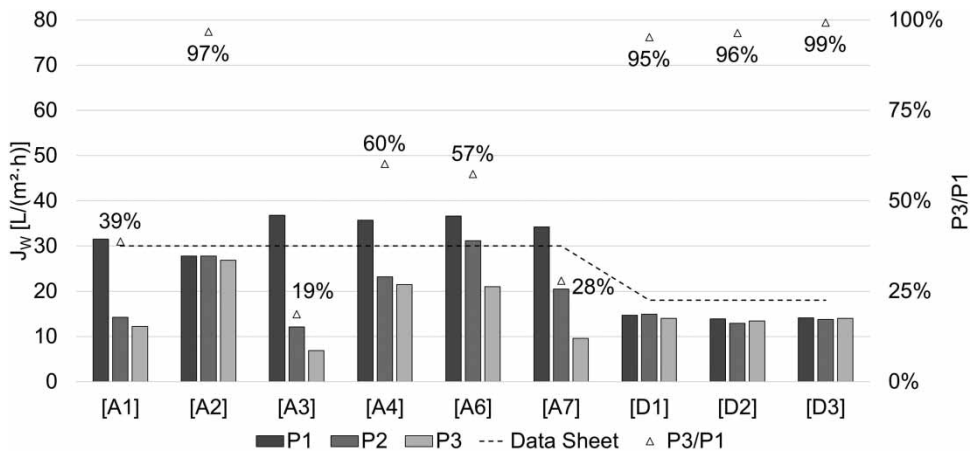


Figure 3 | Permeate flux J_w obtained in standard membrane performance tests before each FO experiment with industrial effluents.

Most probably, membrane performance deteriorated because substances from the industrial effluents deposited either on the membrane surface or accumulated inside the membrane structure. During the test series, the membrane surface could be visually observed because the membrane test cell consisted of acrylic glass. Depositions on the membrane surface were noted with paint shop pre-treatment wastewater as FS (A3, A7), cathodic dip painting rinsing water as FS (A1), and all dairy effluents (D1...D3).

Since the membrane performance declined the most when paint shop pre-treatment wastewater was used, further investigations were carried out. Figure 4 shows the calculated T/M-values of test series A7 when automobile paint shop pre-treatment wastewater was used as FS and cooling tower circulation water as DS. The T/M-value is given for both the FS and the DS side. It is obvious that TSS, iron, nickel, and silicon 'disappear' from the paint shop pre-treatment wastewater (FS) because their T/M-values exceed 1.0 significantly. These substances are either lost due to deposition on the membrane or due to diffusion through the

membrane into the DS. However, only nickel and silicon are increasing in the DS, which can be seen by T/M-values below 1.0. The DS T/M-values show that on this side of the membrane TSS, iron, magnesium, and phosphate were reduced ($T/M > 1$). Only magnesium seems to be passing through the membrane into the FS where the magnesium T/M-value is below 1.0. The other substances probably deposited on the membrane surface or accumulated in the membrane structure.

Cleaning and membrane performance restoration after test series A7

Following test series A7, the membrane was kept in the test cell and different cleaning methods (physical and chemical cleaning, osmotic backwash) were investigated, each followed by a membrane performance test (Table 3). The resulting permeate fluxes are illustrated in Figure 5. As a result, the standard permeate flux could be increased from 3.1 to 10.9 L/(m²·h) by rinsing with deionized water. Taking

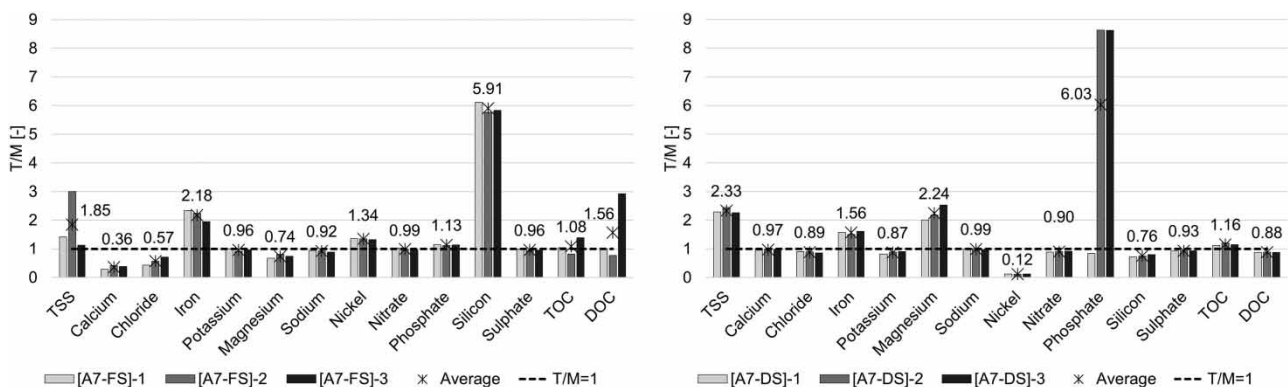


Figure 4 | T/M-values of test series A7 with automobile paint shop pre-treatment wastewater as FS (left) and cooling tower circulation water as DS (right).

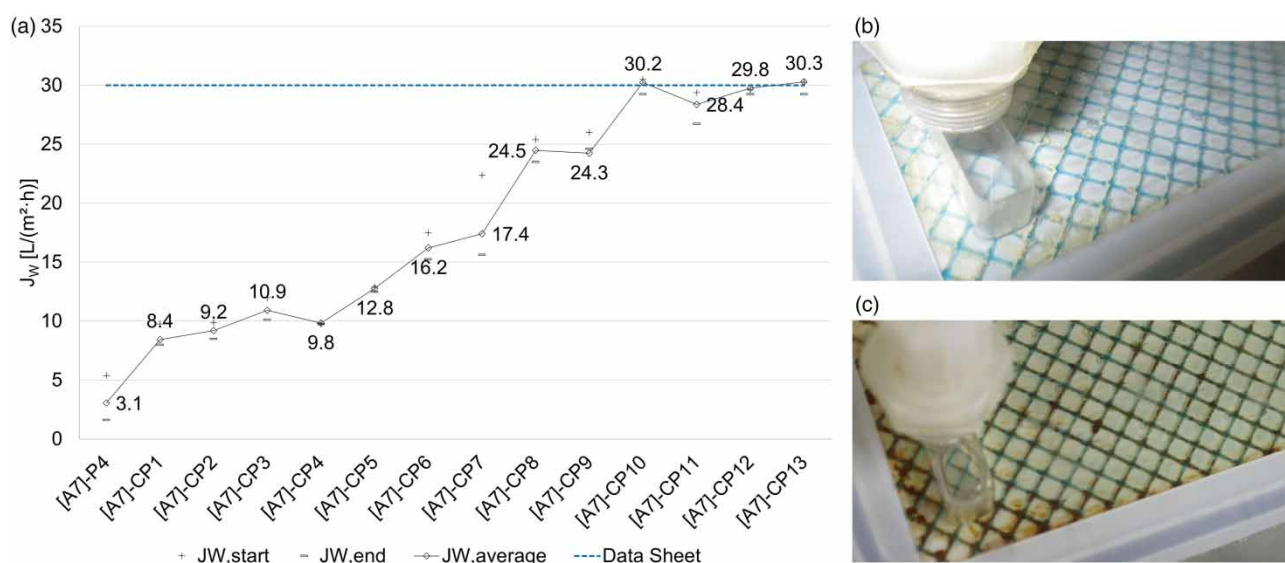


Figure 5 | (a) Permeate flux J_w of membrane performance tests after different cleaning-in-place procedures. (b) Yellow deposits on FS membrane surface after A7 before cleaning procedures. (c) Brown deposits after A7 and cleaning procedures.

into consideration that this cleaning procedure lasted 7 days, it is ineffective. After applying osmotic backwashing, the permeate flux decreased to 9.8 L/(m²·h), showing that this cleaning procedure was also ineffective. Permeate flux increased further to 17.4 L/(m²·h) after rinsing with hydrochloric acid (pH = 3.2 and 2.2), showing a positive effect. The best improvement, however, was achieved after rinsing with deionized water and sodium hydroxide (pH = 11.1) several times. Eventually, the standard permeate flux reached 30.3 L/(m²·h), which equals the value given by the membrane manufacturer in the data sheet.

During the different cleaning processes, the visible deposition layer on the FS side of the membrane was not removed. However, the colour changed from yellow to brown when the membrane was rinsed with sodium hydroxide (see Figure 5(b) and 5(c)). After the experiment, the deposits were removed from the spacer and analysed. The results showed that the deposits consisted mainly of iron. This fact, and the observed colour change, suggests that iron accumulated on the membrane surface as well as in the feed channel and was converted into iron hydroxide during the sodium hydroxide rinsing.

CONCLUSION

Laboratory-scale FO experiments were performed with four effluents from an automobile production site and two effluents from a dairy to investigate the principal applicability of

FO. In general, cathodic dip painting rinsing and wastewater as well as paint shop pre-treatment wastewater from automobile industry appear suitable as FS for FO because the permeate fluxes were 12.1, 19.4 and 7.5 L/(m²·h) combined with 1 mol/L NaCl. Wastewater treatment RO concentrate from the dairy also produced good permeate fluxes of 7.9 (1 mol/L NaCl as DS) and 15.1 L/(m²·h) (cheese brine as DS) when used as FS. Regarding the permeate flux, these four effluents could be treated and concentrated by FO.

According to the permeate flux, only dairy cheese brine is a promising DS with permeate fluxes of 21.0 and 15.1 L/(m²·h) in combination with deionized water and dairy wastewater treatment RO concentrate as FS. Since dairy wastewater treatment RO concentrate also proved to be a suitable FS, a combination of both effluents in FO would be possible, resulting in diluted cheese brine and further concentrated wastewater treatment RO concentrate. For the automobile production site, the investigated draw solutions had only a low osmotic pressure and could not produce a significant permeate flux. For this reason, both the cooling tower circulation water as well as the cathodic dip painting wastewater are unsuitable as DS. In order to apply FO in this automobile production site, other suitable DS need to be found. The following possibilities should be taken into consideration:

- (1) Are there other liquids that are available, e.g. concentrated process chemicals that need to be diluted?
- (2) May an additional DS be used that is circulated and reconcentrated in a separate treatment process? In this

case, clean water is produced which is then applicable for diluting the cooling tower circulation water.

- (3) Is there a way to raise the osmotic pressure of the cooling tower circulation water, e.g. with additives that do not influence cooling performance?
- (4) Could pressure assisted osmosis increase the permeate flux when cooling tower circulation water is used as DS?

Fouling occurred in all of the laboratory-scale experiments. Different cleaning procedures were exemplarily investigated after one test series. Chemical cleaning with sodium hydroxide showed the best effect and permeate flux was restored. The different cleaning procedures should be applicable for automobile as well as dairy wastewater.

All in all, the results show that FO is a potential treatment technology for industrial effluents. Here, one of its main benefits is the combined energy-efficient treatment of two effluents in the same treatment step. Surely, more applications in industry can be found, helping to establish sustainable water usage.

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