

Physical and economical evaluation of laboratory-scale membrane bioreactor by long-term relative cost–benefit analysis

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ABSTRACT

Two laboratory-scale single-stage submerged membrane bioreactors (MBRs) were operated in parallel to examine the effect of different flux conditions and several fouling mitigation methods. After control operation (filtration only), three fouling control methods (relaxation, standard backwash and chemical backwash) at 27 LMH flux and four different flux conditions (54, 36, 27 and 18 LMH) with standard backwash were applied. Physical performance of MBRs was evaluated based on the operational duration to reach maximum transmembrane pressure and the volume of permeate produced during the operational duration. Then relative cost–benefit analysis was carried out. Results showed that the combination of chemical backwash and standard backwash was the most effective for fouling mitigation in terms of physical improvement of MBR performance. However, the combination proved less economical ($400\% + \alpha$ relative cost) than standard backwash alone (343% relative cost), because of the additional cost for pumps and chemicals. It also showed that lower flux (18 LMH) is desirable as it showed better physical performance (1,770% improvement as compared to the highest flux, 54 LMH) and proved more economical than higher flux configuration. Therefore, it is concluded that the operation with standard backwash at the lowest possible flux is the best combination to improve MBR performance as well as long-term cost–benefit.

Key words | cost–benefit analysis, economical evaluation, fouling control, membrane bioreactor, performance evaluation

HIGHLIGHTS

- Rationale

Introduction of new fouling control techniques in MBR operation increases the performance of MBR by reducing the membrane fouling; however, in most cases, an increase in the cost for the application of the new technique is inevitable. So, the improvement of the performance of MBR by the new technique should be justified by an economic point of view. However, many studies focus mainly on high cost, high-performance techniques without economic justification.

Therefore, this research focuses on the interpretation of performance improvement made by several fouling control methods in terms of relative cost as well as physical performance, which is simple but useful to apply in MBR operation.

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- Major finding

Chemical backwash supported by standard backwash showed the highest improvement (874%) in physical performance as compared to control operation. However, the results of the relative cost-benefit analysis showed that the chemical together with standard backwash operation was less economical than standard backwash operation, because it showed higher long-term cost (400% + α) than that of standard backwash operation (343%).

INTRODUCTION

Membrane bioreactor (MBR) technology has been adopted for wastewater treatment and studied extensively worldwide since the advancement of the immersed configuration in the 1990s (Lorhemen *et al.* 2017). In accordance with international progress in wastewater treatment technology, interest in MBR is now rising in the last several years in Pakistan as well to alleviate water-related problems like water scarcity and environmental water degradation. Despite many advantages of MBR (i.e. smaller footprint, better effluent quality, less sludge production, easy operation, etc.), one hindrance of biofouling remains as an unsolved challenge (Guo *et al.* 2012; Kim *et al.* 2014; Nahm *et al.* 2017). To tackle the challenge, many studies were conducted to mitigate the fouling with various approaches. These approaches include physical cleaning methods, such as back flushing (termed in this paper as standard backwash) in which permeate is reversed in the opposite direction, to remove reversible fouling (Krzeminski *et al.* 2017). Another physical cleaning method is air scouring, in which coarse bubble aeration is provided by air pumps, to achieve a significant drop in the transmembrane pressure (TMP) (DeCarolis *et al.* 2007). Relaxation is another physical cleaning technique in which the filtration is stopped for some time and the system relaxes, which can help to prolong the operation for some time (Lade *et al.* 2017). In addition to the physical methods, there are also some chemical cleaning methods which are used for the removal of reversible fouling in MBR. One of these methods is known as chemically enhanced backwash (CEB) in which a mild fouling cleaning chemical, such as sodium hypochlorite, is added to the backwash water (permeate water) (Kimura & Uchida

2019). Other than these, an advanced biological method in combination with physical and chemical cleaning methods is also used these days for decreasing fouling, i.e. Quorum Quenching (QQ) (Weerasekara *et al.* 2016). QQ technique has been used to mitigate biofouling as QQ bacteria are introduced in the reactor either in the form of culture or in the form of immobilized beads that disturb quorum sensing (QS) signals (Waheed *et al.* 2017). It opens a new path and proves to be a new favourable alternative to delay time reaching the maximum TMP (Maqbool *et al.* 2015).

Including all these approaches, physical cleaning methods, chemical cleaning methods (use of various cleaning agents, such as NaOCl, acids, etc.), physico-chemical methods (combination of aforementioned two) and biological methods (cleaning mixtures based on microbial cultures or enzymes) (Cinar *et al.* 2016), an introduction of new fouling control techniques in MBR operation may further increase its overall performance. However, the addition of specific cost is required for the application of the new technique. Hence, performance improvement of MBR should be backed up by economic justification through a cost-benefit analysis (Xiao *et al.* 2019). Therefore, this study was designed with two distinct aims. Firstly, to find out the best combination of fouling control methods and better flux conditions based on the results of a laboratory-scale single-stage submerged MBR with various operational conditions. Secondly, to suggest an easy methodology showing how to justify the physical improvement of MBR by the relative cost involved in the improvement. The main parameters are performance improvement of MBR in terms of flux and life cycle plus the economic feasibility of each of the fouling control methods.

METHODOLOGY

MBR setup, operation and analysis

The two series of laboratory-scale MBR plants were constructed and operated in parallel to treat synthetic wastewater that simulates medium strength domestic wastewater. It was prepared by 10 times dilution with tap water from a stock wastewater solution that was 10 times stronger than the intended concentration. The stock wastewater was made of Glucose 1,200 mg/L, Peptone 900 mg/L, Yeast extract 120 mg/L, $(\text{NH}_4)_2\text{SO}_4$ 960 mg/L, KH_2PO_4 170 mg/L, NaHCO_3 3,000 mg/L, $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$ 24 mg/L, $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ 240 mg/L, $\text{MnSO}_4 \cdot 5\text{H}_2\text{O}$ 21.6 mg/L and $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$ 1.2 mg/L as per composition described in another study (Weerasekara *et al.* 2014). It was stored at 4 °C in a refrigerator and used as required. Actual values of BOD, COD and $\text{NH}_4^+\text{-N}$ of the influent of MBR were 178 ± 12 mg/L, 223 ± 15 mg/L and 28 ± 2.5 mg/L, respectively. The seed sludge was obtained from a pilot-scale MBR plant at National University of Science and Technology, Islamabad, Pakistan. The MLSS was grown from around 2,000 mg/L in the beginning to 8,000 mg/L during the stabilization phase (3 months). It was maintained at 8,000 mg/L by withdrawing excess sludge whenever the concentration became higher. Two reactors were used in parallel to operate MBRs with different conditions. MBRs were operated with a constant flow mode until they reached a maximum TMP value of 33 kPa (4.8 psi) as recommended by the membrane

manufacturer. Whenever the TMP of the MBR reached the maximum limit, it was considered that the membrane module became fouled. All the operational parameters including F/M ratio, aeration flow rates, influent, effluent (i.e. permeate) and backflush were maintained within the range shown in Table 1 during all MBR operations. Then all the research variables were tested when the MBRs reached a steady state. The specifications of MBR plants and membrane material are shown in Table 1. Combined schematic diagram of the MBR plants and membrane module used in this research are shown in Figure 1. All the valves and pumps were controlled by programmable logic controller.

Water quality parameters, like BOD, COD and $\text{NH}_4^+\text{-N}$ and operational parameters, like MLSS, MLVSS, free chlorine, TMP (Sper Scientific data logging manometer, Model# 840099) were monitored regularly. They were all determined by Standard Methods for the Examination of Water and Wastewater (APHA 2012). All operating parameters were kept constant (unless separately mentioned) to estimate the effect of different variables on the MBR performance.

Research variables

In order to improve MBR performance and lifespan of membranes, many approaches have been developed by researchers. However, in this research, the effect of flux on membrane fouling and effect of three fouling control techniques, among the approaches already developed, were

Table 1 | Specifications of MBR and membrane material

MBR information		Membrane information	
Type of MBR	Single stage, submerged	Manufacturer	PHILOS Korea
Reactor material	Poly acrylic	Membrane material	Hydrophilic PVDF
Working volume	8.1 L/reactor	Supporting material	Polyester
Permeate flow rate	26 mL/min	Inner diameter	1.0 mm
Backflush flow rate	52 mL/min	Outer diameter	2.3 mm
HRT	5.2 h	Pore size	0.1 μm
SRT	17–20 days	Module design	Loop shape
MLSS	8,000 mg/L	Effective length	50 cm/fibre
F/M ratio	0.12–0.14 g BOD/gVSS-day	Effective surface area	289–867 cm^2 /reactor
Air flow rate/reactor	3 L/min	Flux	18–54 LMH

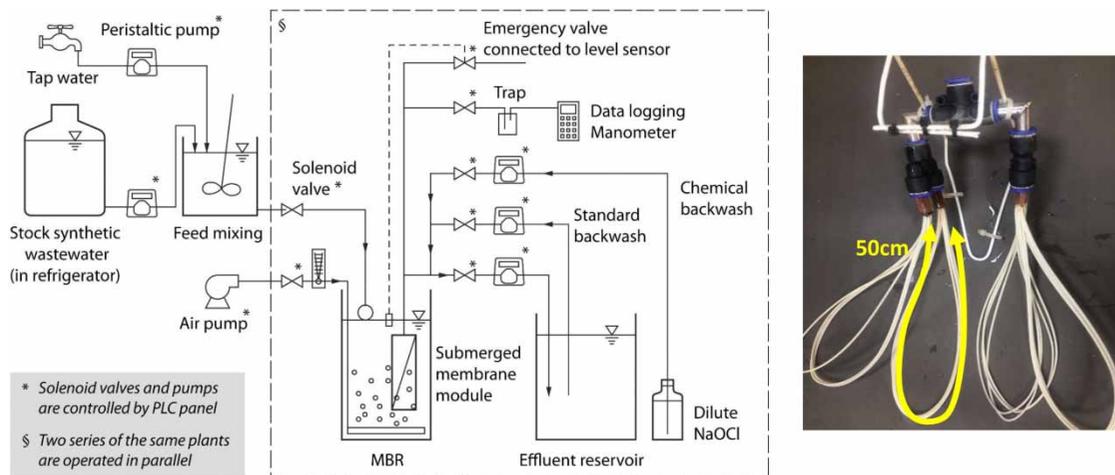


Figure 1 | MBR plant and membrane module.

selected as research variables (Table 2). Physical performance of the MBR was determined by the length of operational duration until the membrane module gets fouled through the observation of maximum TMP as suggested by the manufacturer (4.8 psi = 33 kPa). Total production of permeate (amount of treated water) was calculated with operational duration and flow rate followed by the deduction of backwash water which was used from the stored treated water.

The operation of ‘filtration’ was set as a control operation where continuous filtration was provided without applying any fouling control technique. The first fouling control technique was ‘relaxation’ in which membranes get relaxed when filtration stops for 1 min after 10 min

filtration, while biomass attached on the membranes may get detached by air bubbles. Relaxation for 1 min after 10 min requires ‘giving up 10% of operation time’ for treated water production. The relaxation mode does not need extra cost. As a second fouling control technique, a simple backwash was chosen as it is a widely utilized technique and named as ‘standard backwash’ to contrast it with another fouling control method, backwash with the addition of chemicals. The standard backwash was done with permeate (effluent) produced by the MBR during operation for 1 min with double flow rate and with the reverse direction of permeate after every 10 min filtration. Standard backwash line is shown in Figure 1. It means ‘giving up 10% of time and investing 20% of treated water’ which involves one

Table 2 | Research variables used in this study

Research variable 1		Research variable 2	
Fouling control method ^a	Operation method	Flux ^b	Effective surface area of membrane module
Filtration	No fouling control Continuous filtration only	18 LMH	867 cm ²
Relaxation	Stop filtration for 1 min after 10 min filtration	27 LMH	578 cm ²
Standard Backwash	1 min backwash after 10 min filtration Backwash at double flow rate in reverse direction	36 LMH	434 cm ²
Chemical Backwash	1 min twice a day in-line chemical backwash (500 ppm NaOCl) with standard backwash	54 LMH	289 cm ²

^aDifferent fouling control operations were done at 27 LMH condition.

^bDifferent flux operations were done with standard backwash.

additional pump for the backwash to improve the performance of MBR. The last fouling control technique was 'chemical backwash' which includes the addition of a small amount of chemical in the backwash water (also known as CEB). According to the membrane manufacturer's suggestion, 500 ppm NaOCl solution was used for the chemical backwash. While the standard backwash was being repeated during the operation, twice a day, the standard backwashes were replaced with this chemical backwash. This requires 'giving up 10% of time and investing 20% of treated water' together with two additional pumps for the standard backwash and chemical backwash, and extra chemical cost.

Relative cost–benefit analysis

For construction and operation of MBR plant, the major cost of concern is for initial membrane installation, replacement after its lifespan finishes and initial pump installation and energy cost for pump operation. Energy consumption for aeration is one of the major concerns (Lo *et al.* 2015). However, it was not considered here since the aeration rate was fixed in this research to maintain a minimum dissolved oxygen concentration of 2 mg/L and maintain proper mixing of sludge inside the bioreactor. Relative economic effects of each operation

were determined by relative cost, based on initial cost and replacement cost of membrane and pumps that are closely related to the fouling control. Membrane replacement cost was calculated based on the assumption that the membrane will get deteriorated by frequently experiencing extreme conditions, i.e. fouling and recovery cleaning (Puspitasari *et al.* 2010). The more frequent fouling and recovery cleaning, the quicker the membrane replacement. The relative cost was expressed in percentage units for easy comparison. And scaling effect to bigger scales was not considered here as this research is limited to the laboratory-scale MBR operation. But this relative cost approach can be applied to any scale when data for physical performance and related costs are available.

RESULTS AND DISCUSSION

Removal efficiency of COD, BOD and $\text{NH}_4^+\text{-N}$

Average removal efficiencies of COD, BOD and $\text{NH}_4^+\text{-N}$ were fairly good at 91.7, 97.2 and 98.9%, respectively, throughout this research period (Table 3). There were minor differences between operations which are statistically insignificant. *P*-values of One-way ANOVA tests for all the

Table 3 | Average removal efficiencies of BOD, COD and $\text{NH}_4^+\text{-N}$ for of each operation

Operations	COD			BOD			$\text{NH}_4^+\text{-N}$		
	Removal (%)	<i>n</i> ^a	Stdev ^b	Removal (%)	<i>n</i> ^a	Stdev ^b	Removal (%)	<i>n</i> ^a	Stdev ^b
Total	91.7	89	5.3	97.2	48	2.7	98.9	46	1.8
Filtration (control)	89.6	4	3.2	97.7	4	0.6	96.3	4	2.5
Relaxation	89.7	7	2.4	97.0	5	0.9	98.9	4	0.8
Standard backwash	92.4	9	2.1	97.9	5	0.9	98.6	7	0.6
Chemical + standard backwash	92.2	10	1.7	99.2	6	0.5	99.5	6	0.2
54 LMH	94.1	8	2.7	98.8	4	0.9	99.5	4	0.2
36 LMH	94.2	8	2.2	98.2	4	1.4	99.5	4	0.3
27 LMH	90.2	10	5.0	96.8	10	3.2	99.5	8	0.1
18 LMH	91.2	33	6.1	94.8	10	3.4	98.9	9	0.6
One-way ANOVA	<i>p</i> = 0.520 > 0.05			<i>p</i> = 0.079 > 0.05			<i>p</i> = 0.406 > 0.05		

^a*n* = sample size.

^bStdev = standard deviation of sample.

operations were greater than 0.05. It can be said that different flux conditions and different fouling control techniques including chemical addition in backwash water did not show any negative impact on the effluent quality of MBR. Since under all the different operational conditions, the removal efficiencies were almost the same, hence it was decided that the base of performance comparison of MBRs would be the quantity of permeate produced. So, no further investigation of effluent quality would be done in this study as it has been already proved by many researchers (Wen et al. 2004; Chen & Liu 2012).

TMP profiles of different fouling control methods

It was observed that the 1st operation (filtration only; a control operation) worked for an average of 1.75 days (average of 3 cycles) when no fouling control method was applied as shown in Figure 2. The 2nd operation worked for 2.32 days (average of 2 cycles) when 1 min relaxation was repeatedly applied after 10 min filtration. The 3rd operation worked for 16.4 days when 1 min standard backwash was repeatedly applied after 10 min filtration. The last operation continued for 23.4 days when chemical backwash was added twice a

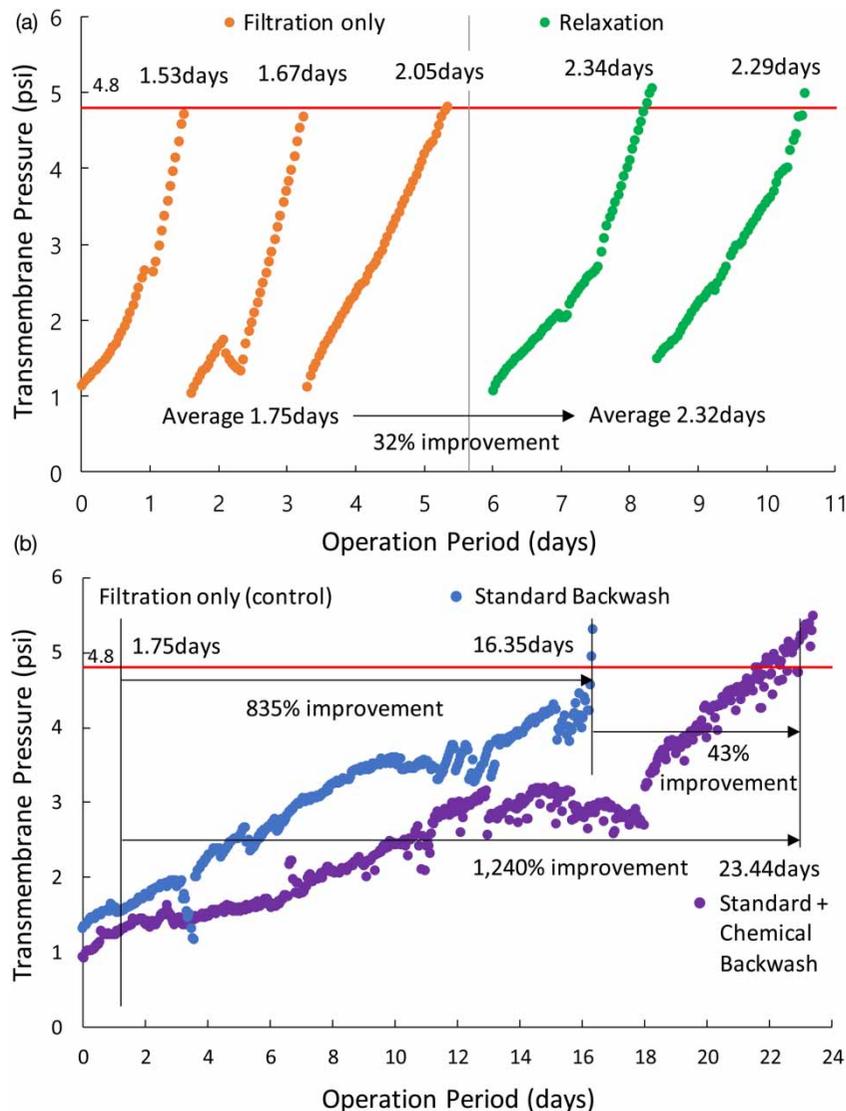


Figure 2 | TMP profiles of different fouling control operations. (a) Filtration only and relaxation, (b) standard backwash and chemical backwash.

day on the top of standard backwash. Application of relaxation extended operational duration by 0.57 day (1.75 days → 2.32 days, 32%), standard backwash extended it by 14.6 days (1.75 days → 16.35 days, 835%) and chemical backwash together with standard backwash extended it by 21.69 days (1.75 days → 23.44 days, 1,240%). But because the improvement in the last operation was from the combination of standard backwash and chemical backwash, the effect of chemical backwash alone needs to be separated from the combined effect. When the last operation was compared with standard backwash operation, the improvement of operational duration was 7.09 days (16.35 days → 23.44 days, 43%). These improvements in operational durations are shown in Figure 2. Therefore, the effect of standard backwash was shown to be the greatest as an individual fouling control method. So, it was selected for further investigation at different flux conditions.

TMP profiles of different flux operations

All different flux operations were conducted under standard backwash conditions. It was observed that MBR worked for average 2.90 days (average of 3 cycles) at 54 LMH, 5.29 days (average of 2 cycles) at 36 LMH, 14.14 days (average of 2 cycles) at 27 LMH and 54.29 days at 18 LMH as shown in Figure 3. When 50% greater membrane material was used to reduce flux (8 fibres at 54 LMH → 12 fibres at 36 LMH), MBR worked 2.39 days longer (2.90 days → 5.29 days, 82%). When 100% greater membrane material was used (8 fibres at 54 LMH → 16 fibres at 27 LMH), MBR worked 11.23 days longer (2.90 days → 14.14 days, 387%). When 200% greater membrane material was used (8 fibres at 54 LMH → 24 fibres at 18 LMH), MBR worked 51.38 days longer (2.90 days → 54.29 days, 1,770%).

This result clearly shows that flux is one of the most important driving forces to accelerate fouling on membranes. This is in accordance with the results of other researchers (Drews *et al.* 2008). However, flux cannot be lowered infinitely because membrane installation cost would correspondingly increase to lower the flux. Therefore, it is necessary to design the flux of MBR to be low enough while keeping the other conditions optimum with economic consideration.

Comparison of production of treated water

Permeate production per cycle of each operation was calculated by flow rate and operational duration with due consideration to the relaxation or backwash time and the volume of water used for backwash. Backwash flow rate was double the permeate flux.

As shown in Figure 4(a), the application of relaxation mode improved the production slightly by 14% compared to control operation (filtration only). Application of standard backwash improved the production greatly by 580% due to the detaching effect of backwash flow against loosely bound biofilm on the membrane. As a reward for 20% investment, 580% more effluent was produced which can lead to 580% longer lifespan of membrane. Addition of chemical backwash on top of standard backwash improved it by 874%. The chemical oxidant interfered with the growth of biofilm on the membrane and it further mitigated fouling. Individual improvement by chemical backwash alone was 43% compared to standard backwash operation. Therefore, standard backwash was found to be the most useful fouling control method among the options investigated in this research.

Under the standard backwash condition, the effect of flux on operational duration and production was investigated. As shown in Figure 4(b), 36 LMH operation produced 82% greater water throughput than 54 LMH operation, 27 LMH produced 387% greater and 18 LMH produced 1,770% greater production. A drastic increment of production was observed between 27 and 18 LMH. However, this result does not mean that the lowest flux (i.e. 18 LMH) is always beneficial, rather it implies that there must be a certain point which can maximize the benefit with a small investment. It is confirmed that flow velocity toward membrane pores is one of the important driving forces to accelerate biofilm formation (Dreszer *et al.* 2014). However, it depends on many other factors as well, e.g. characteristics of sludge and wastewater and so on (Han *et al.* 2005; Huang *et al.* 2011).

Relative cost-benefit analysis

For the comparison of fouling control techniques, flux was kept constant. Membrane surface area is the same

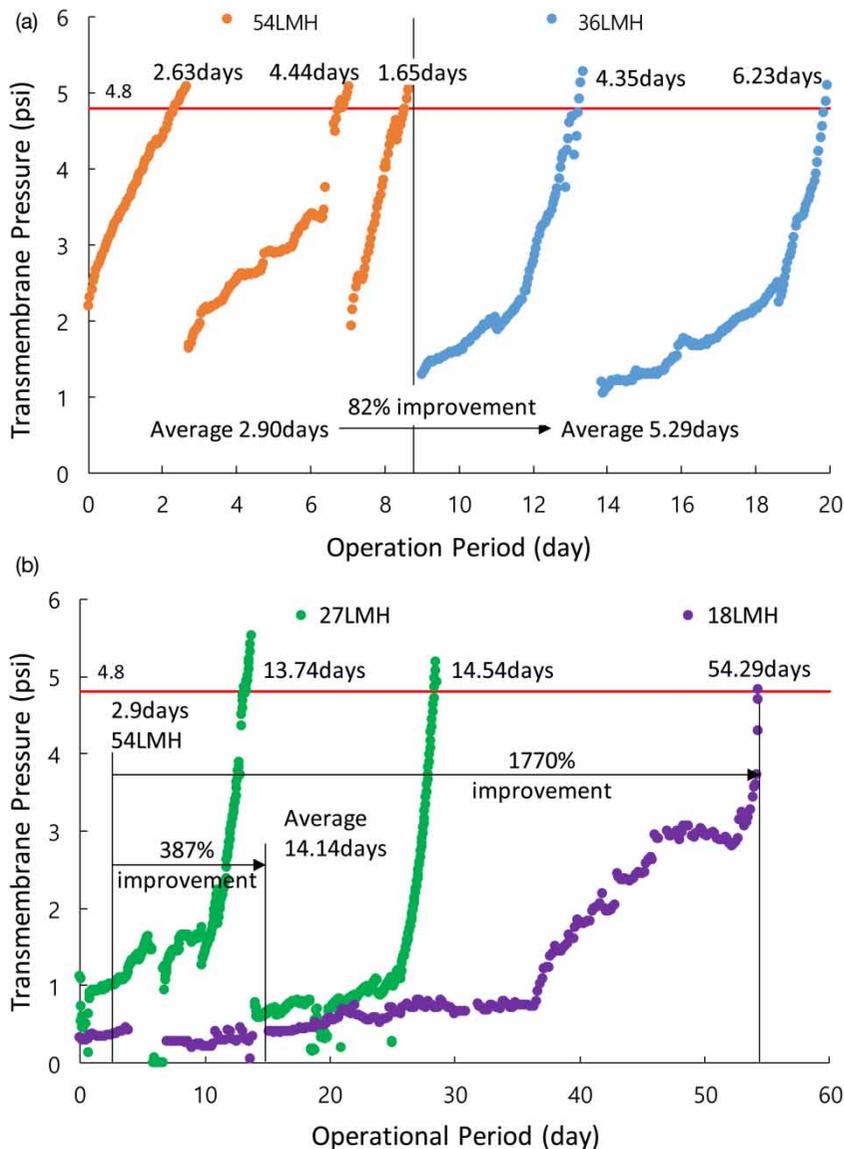


Figure 3 | TMP profiles of different flux operations. (a) 54 and 36 LMH condition, (b) 27 and 18 LMH condition.

for all operations, which means the initial membrane installation cost is the same. So the initial cost for membrane installation is insignificant in relative cost. Significant difference is from membrane replacement because the lifespan of membrane will vary according to different fouling phenomena. To utilize standard backwash and chemical backwash, additional pumps are required. When standard backwash is applied, a designated backwash pump with the same capacity with a permeate suction pump is required, although switching-

on time of the pump is less while the flow rate is usually 100–200% of the permeate flow. When chemical backwash is added on top of standard backwash, a designated chemical pump is also required. Capacity of a chemical pump depends on design. High concentration of chemicals can be injected into the backwash pipe line with a smaller chemical pump. However, in this case, another cost is involved in monitoring chemical concentration and mixing. To simplify the cost calculation, the estimation was made utilizing the same capacity of

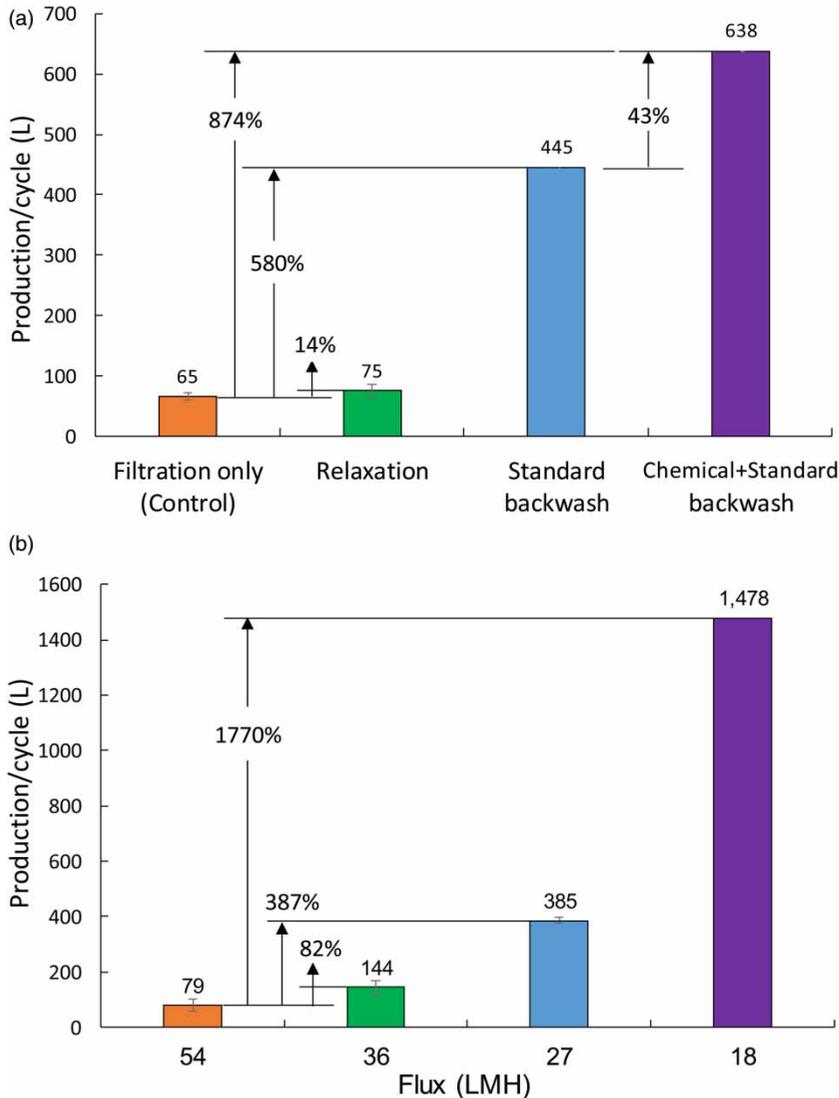


Figure 4 | Improvement of production of treated water. (a) By different fouling control methods, (b) by different flux with standard backwash.

the pump with the permeate suction pump, as used in the MBR setup of this study, to pump appropriate concentration (not high concentration) of chemical to the membrane module. So, in order to conduct a cost-benefit analysis, the cost of three peristaltic pumps with the same specification (for permeate suction, standard backwash and chemical backwash) was used.

As shown in Figure 5(a), initial pump costs for both filtration-only operation and relaxation operation are equal to 100%. However, it increases to 200% with the application of standard backwash and 300% with the application of chemical backwash. On the other hand,

the operation with chemical backwash works longer than others. It will experience fewer extreme conditions (i.e. fouling and recovery cleaning) and the time to replace membrane gets delayed. When the time comes, all the membranes that were installed initially should be replaced (100% replacement cost). Standard backwash operation gets fouled slightly earlier than chemical backwash operation, it experiences more frequent extreme conditions, which lead to a quicker replacement of membranes. Relaxation operation and filtration-only operation become fouled further earlier and more frequent extreme conditions need to be faced which leads to a much

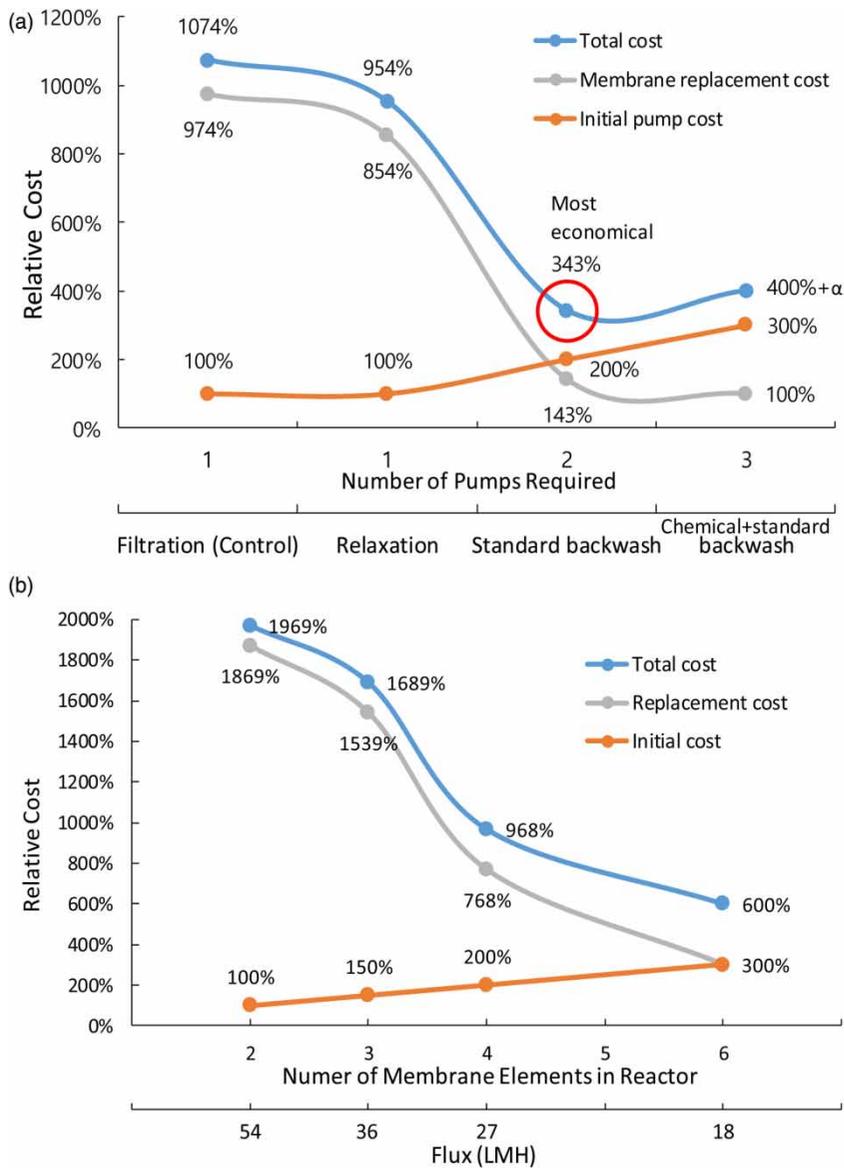


Figure 5 | Relative long-term cost of different operation. (a) By different fouling control methods, (b) by different flux.

quicker replacement of membranes. Therefore, the relative cost of membrane replacement is inversely proportional to relative production. Relative cost caused by quicker replacement was calculated to be 143, 854 and 974% for standard backwash, relaxation and filtration only operation respectively, as compared to the longest operation (chemical + standard backwash). When an MBR plant runs for a long period, total relative costs for chemical + standard backwash, standard backwash, relaxation and filtration-only operations are then

400% + α (α : additional cost for chemical), 343%, 954% and 1,074% respectively. Although the operational duration and production of chemical + standard backwash were the greatest, it was found to be less economical than that of standard backwash in long-term operation because of the higher initial cost for chemical pump and additional cost for chemicals. Therefore, standard backwash operation was found to be the most economical for long-term operation as its total relative cost is shown to be the least (circle in Figure 5(a)).

As shown in Figure 5(b), initial membrane cost increases in accordance with a decrease in flux (100, 150, 200 and 300% for 54 LMH, 36 LMH, 27 LMH and 18 LMH, respectively). When a time comes to replace all the membrane of 18 LMH operation, the same amount of membrane (300%) that was installed initially should be replaced. During the same time, 27 LMH, 36 LMH and 54 LMH operations get fouled more frequently and lead to more frequent replacement. So, the relative replacement costs were calculated to be 768, 1,539 and 1,869% for 27 LMH, 36 LMH and 54 LMH operations, respectively. Total relative costs for 18 LMH, 27 LMH, 36 LMH and 54 LMH were then 600, 986, 1,689 and 1,969%, respectively. It was found that the lowest flux 18 LMH operation is more economical than the other operations in the long term. As a result of relative cost-benefit analysis, the combination of standard backwash and 18 LMH flux would be the best operational condition to maximize MBR performance by decreasing long-term cost.

However, this suggestion is limited to the conditions which are included in this research. Effect of chemical cleaning can vary by introducing different chemical backwash schemes (different concentration, frequency of application, different chemicals, etc.). Introduction of different biofouling control methods may result in different relative cost and conclusion from this study. It is suggested that any physical improvement of performance needs to be justified by the initial and long-term costs.

CONCLUSION

From the result of performance evaluation of fouling control methods, two chemical backwashes per day supported by standard backwash can be considered as the best anti-fouling technique as it showed the highest improvement (874%) as compared to control operation (filtration only). However, it was found through relative cost-benefit analysis that standard backwash operation was the most economical in long-term operation, although its performance improvement (580%) was not as high as a chemical with standard backwash, because the relative long-term cost for standard backwash operation (343%) was smaller than that of chemical together with standard backwash operation ($400\% + \alpha$). The lowest possible flux is recommended to

improve MBR performance and to reduce long-term cost as 18 LMH operation showed the greatest improvement (1,770%) compared to 54 LMH operation and the smallest relative long-term cost. Therefore, it is concluded that operation with standard backwash as a fouling control method at the lowest possible flux is the best combination to improve MBR performance in terms of physical improvement as well as long-term cost. It is also recommended that any new fouling control method should be justified not only by physical performance improvement but also by cost-benefit analysis. Although this study does not indicate any scaling effect for readily usable cost-benefit analysis to full-scale plants, this approach may be useful to justify any new fouling technique in the future of MBR research.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES

- American Public Health Association/American Water Works Association/Water Environment Federation 2012 *Standard Methods for the Examination of Water and Wastewater*, 22nd edn. AWWA, Washington, DC, USA.
- Chen, W. & Liu, J. 2012 [The possibility and applicability of coagulation-MBR hybrid system in reclamation of dairy wastewater](#). *Desalination* **285**, 226–231.
- Cinar, O., Kizilet, A., Isik, O., Čemanović, A. & Akif, M. 2016 A review on dynamic membrane bioreactors: comparison of membrane bioreactors and different support materials, transmembrane pressure. In: *Proceedings of International Conference on Engineering and Natural Sciences*, Sarajevo, pp. 2505–2513.

- DeCarolis, J. F. & Adham, S. 2007 Performance investigation of membrane bioreactor systems during municipal wastewater reclamation. *Water Environment Research* **79** (13), 2536–2550.
- Dreszer, C., Wexler, A. D., Drusová, S., Overdijk, T., Zwijnenburg, A., Flemming, H. C. & Vrouwenvelder, J. S. 2014 *In-situ* biofilm characterization in membrane systems using optical coherence tomography: formation, structure, detachment and impact of flux change. *Water Research* **67**, 243–254.
- Draws, A., Vocks, M., Bracklow, U., Iversen, V. & Kraume, M. 2008 Does fouling in MBRs depend on SMP? *Desalination* **231** (1–3), 141–149.
- Guo, W., Ngo, H. H. & Li, J. 2012 A mini-review on membrane fouling. *Bioresource Technology* **122**, 27–34.
- Han, S. S., Bae, T. H., Jang, G. G. & Tak, T. M. 2005 Influence of sludge retention time on membrane fouling and bioactivities in membrane bioreactor system. *Process Biochemistry* **40** (7), 2393–2400.
- Huang, Z., Ong, S. L. & Ng, H. Y. 2011 Submerged anaerobic membrane bioreactor for low-strength wastewater treatment: effect of HRT and SRT on treatment performance and membrane fouling. *Water Research* **45** (2), 705–713.
- Kim, J., Shin, J., Kim, H., Lee, J. Y., Yoon, M. H., Won, S., Lee, B. C. & Song, K. G. 2014 Membrane fouling control using a rotary disk in a submerged anaerobic membrane sponge bioreactor. *Bioresource Technology* **172**, 321–327.
- Kimura, K. & Uchida, H. 2019 Intensive membrane cleaning for MBRs equipped with flat-sheet ceramic membranes: controlling negative effects of chemical reagents used for membrane cleaning. *Water Research* **150**, 21–28.
- Krzeminski, P., Leverette, L., Malamis, S. & Katsou, E. 2017 Membrane bioreactors – a review on recent developments in energy reduction, fouling control, novel configurations, LCA and market prospects. *Journal of Membrane Science* **527**, 207–227.
- Lade, H., Song, W. J., Yu, Y. J., Ryu, J. H., Arthanareeswaran, G. & Kweon, J. H. 2017 Exploring the potential of curcumin for control of N-acyl homoserine lactone-mediated biofouling in membrane bioreactors for wastewater treatment. *RSC Advances* **7** (27), 16392–16400.
- Lo, C. H., McAdam, E. & Judd, S. 2015 The cost of a small membrane bioreactor. *Water Science and Technology* **72** (10), 1739–1746.
- Lorhemen, O. T., Hamza, R. A. & Tay, J. H. 2017 Membrane fouling control in membrane bioreactors (MBRs) using granular materials. *Bioresource Technology* **240**, 9–24.
- Maqbool, T., Khan, S. J., Waheed, H., Lee, C. H., Hashmi, I. & Iqbal, H. 2015 Membrane biofouling retardation and improved sludge characteristics using quorum quenching bacteria in submerged membrane bioreactor. *Journal of Membrane Science* **483**, 75–83.
- Nahm, C. H., Choi, D. C., Kwon, H., Lee, S., Lee, S. H., Lee, K. & Park, P. K. 2017 Application of quorum quenching bacteria entrapping sheets to enhance biofouling control in a membrane bioreactor with a hollow fiber module. *Journal of Membrane Science* **526**, 264–271.
- Puspitasari, V., Granville, A., Le-Clech, P. & Chen, V. 2010 Cleaning and ageing effect of sodium hypochlorite on polyvinylidene fluoride (PVDF) membrane. *Separation and Purification Technology* **72** (3), 301–308.
- Waheed, H., Xiao, Y., Hashmi, I., Stuckey, D. & Zhou, Y. 2017 Insights into quorum quenching mechanisms to control membrane biofouling under changing organic loading rates. *Chemosphere* **182**, 40–47.
- Weerasekara, N. A., Choo, K. H. & Lee, C. H. 2014 Hybridization of physical cleaning and quorum quenching to minimize membrane biofouling and energy consumption in a membrane bioreactor. *Water Research* **67**, 1–10.
- Weerasekara, N. A., Choo, K. H. & Lee, C. H. 2016 Biofouling control: bacterial quorum quenching versus chlorination in membrane bioreactors. *Water Research* **103**, 293–301.
- Wen, X., Ding, H., Huang, X. & Liu, R. 2004 Treatment of hospital wastewater using a submerged membrane bioreactor. *Process Biochemistry* **39** (11), 1427–1431.
- Xiao, K., Liang, S., Wang, X., Chen, C. & Huang, X. 2019 Current state and challenges of full-scale membrane bioreactor applications: a critical review. *Bioresource Technology* **271**, 473–481.

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