A new backwash strategy for reducing the cost of an immersed ultrafiltration system by restricting cake layer breakage

Fangshu Qu, Xiaolian Li, Junguo He, Zhihui Pan, Yan Zhao, Hongwei Rong, Guibai Li and Huarong Yu

ABSTRACT

Ultrafiltration (UF) is increasingly used for potable water treatment, but membrane fouling necessitates the application of periodical backwash, which increases running cost. A new backwash strategy, in which air scouring was only applied with sludge water discharging, was proposed to improve backwash performance in a water plant using UF. Four gravity-driven UF systems were simultaneously run at increasing air scouring intervals (3–24 hours) and sludge water discharging intervals (12–24 hours). The membrane fluxes were monitored to assess membrane fouling and the mix solution turbidity was also monitored to investigate deposition of particles. The results indicated that membrane fouling was not aggravated by the extension of air scouring and sludge water discharging intervals. Water backwash on its own induced a shift of particle deposition from the membrane surface to the bottom of the membrane tank due to limited cake layer breakage, enabling the extension of sludge water discharging intervals. For the gravity-driven system investigated, the running cost, including energy, water and chemical demand, was reduced by 16.67% as the air scouring and sludge water discharging intervals increased from 3 hours to 24 hours and from 12 hours to 24 hours, respectively.

Key words | backwash, cake layer, membrane fouling, running cost, ultrafiltration

Fangshu Qu
Xiaolian Li
Junguo He
Zhihui Pan
Hongwei Rong
Huarong Yu (corresponding author)
School of Civil Engineering,
Guangzhou University,
Guangzhou, 510006,
China
E-mail: *huarongyu@gmail.com*

Yan Zhao
Guangdong GDH Water Co. Ltd,
Shenzhen, 518021,
China

Guibai Li
School of Environment,
Harbin Institute of Technology,
Harbin, 150091,
China

INTRODUCTION

Because of outstanding advantages, such as high-quality produced water and small footprint, membrane technology is increasingly applied in potable water supply to meet stringent requirements in water quality (Van Der Bruggen *et al.* 2003). In particular, ultrafiltration (UF) can completely retain particles, colloids, bacteria and pathogens, substantially improving water security (Jacangelo *et al.* 1997). However, deposition of particles, colloids and natural organic matter on the membrane surface during filtration usually causes severe fouling in long-term operation, resulting in increased energy demand and thus restricted engineering application (Zhang *et al.* 2015; Li *et al.* 2019).

To maintain the stable running of a UF system, periodic physical cleaning is used to remove deposited foulants and to restore membrane permeability. In full-scale applications, the fouled membrane is typically backwashed with the produced water at a flux several times (2–5) bigger than the permeate flux (Li *et al.* 2010; Chang *et al.* 2017). In addition, air scouring is widely used to improve backwash performance, particularly for immersed UF systems (Ye *et al.* 2010; Du *et al.* 2016). However, in some cases, minor or even adverse impacts of air scouring on backwash efficiency has also been reported in the literature. Ye *et al.* (2011) demonstrated that air-scouring-aided backwash induced the deposition of more highly resistant components over multiple filtration and backwash cycles due to the potential fractionation of foulant species at high air scouring rates. To find an optimum backwash

doi: 10.2166/ws.2020.060

strategy, a variety of backwash parameters, such as backwash interval, intensity and duration, have been investigated in terms of backwash efficiency. Generally, shorter intervals, higher intensities and longer durations are favourable for fouling control, and less improvement can be anticipated with further increases in backwash intensity beyond the optimum point (De Souza & Basu 2013). In addition, backwash water composition has also been found to affect backwash performance, with deionized water, salt solution and reverse osmosis brine considered as alternatives for the membrane permeate (Li *et al.* 2009; Chang *et al.* 2016). However, there is a trade-off between backwash performance and running costs, because increased backwash intensity and duration result in more energy and water consumption.

The immersed hollow-fiber UF system is extensively applied in potable water treatment and membrane bioreactors due to low energy demand resulting from low applied pressure (<0.1 MPa) (Miyoshi *et al.* 2016; Chang *et al.* 2019). For immersed UF systems, the sludge water is not discharged every time a backwash is performed, so as to improve water production efficiency. In our previous work, we demonstrated that increased sludge water discharging could benefit control of both reversible and irreversible fouling during reservoir water treatment by UF but resulted in increased self-used water (Bai *et al.* 2013). However, the foulants in the sludge water may re-deposit on the membrane in the subsequent filtration. The retained foulants may repeatedly deposit on the membrane surface during filtration and break up during backwash, resulting in increased energy demand. It has been reported that changes in cake height, composition and structure were affected by the hydrodynamics of the backwash and air scouring (Ye *et al.* 2011). Hence, the interval for sludge water discharging should be taken into consideration as well as backwash intensity and duration. To the best of our knowledge, the mutual influence of water backwash, air scouring and sludge water discharging is rarely investigated.

In this work, a new backwash strategy, with air scouring only applied with sludge water discharging, was proposed to improve backwash performance. Moreover, the intervals for sludge water discharging were extended to assess changes in fouling evolution and running costs. The variation in the turbidity of the mix solution at different depths in the UF tank were monitored to investigate the deposition pathway of the retained particles and colloids.

METHODS AND MATERIALS

Raw water quality

The investigation was performed in a full-scale potable plant in the dry season. The water plant was located in the southern part of China (Zhaoqing city, Guangdong province). The raw water for the plant was taken from the Dongjiang river, and the water quality parameters are shown in Table 1. The water temperature during the experimental period varied in a range of 24.0–31.2 °C, and the raw water turbidity was between 6.2 and 12.5 NTU. In the rainy season, the raw water turbidity is substantially higher, even exceeding 1,000 NTU. Under these circumstances, the operational parameters for the pretreatment system would be adjusted, i.e. increasing coagulant doses and increasing the sludge water discharging frequency of the sedimentation tanks, so that the UF system would not be severely impacted. The organic and nutrient pollution were quite low. Dissolved organic carbon (DOC) and ammonia were in the ranges of 1.90–3.68 mg/L and 0.12–0.60 mg/L, respectively.

UF system and running parameters

In the water plant investigated, a hybrid drinking water treatment process was applied including coagulation, sedimentation, UF and chlorine disinfection. Polyaluminium chloride was dosed at a concentration of 4 mg Al/L^{-1}. An inclined tube sedimentation tank was used for flocs to settle for about 5 min. Subsequently, the UF was used to treat the settled

Table 1 | Quality indexes for raw water in the experimental period

Indexes	Ranges
Temperature (°C)	24.0–31.2
pH	6.9–7.2
Turbidity (NTU)	6.2–12.5
DOC (mg/L)	1.90–3.68
Ammonia (mg/L)	0.12–0.60
Dissolved oxygen (mg/L)	5.7–8.7

water instead of sand filtration. The capacity of the plant was 20,000 m^3/day with four submerged UF systems. The total membrane surface was about 32,000 m^2. The hollow-fiber UF membrane (LJ2A-2000-V200), which was purchased from Litree Co. Ltd., was made of PVC alloy with a molecular weight cut-off (MWCO) of 50 kDa. The inner and external diameters of the membrane fiber were 1.0 and 1.6 mm, respectively. As shown in Figure 1, the UF system was run in a gravity-driven mode using a water-level difference of 3.0 m, which could provide a transmembrane pressure (TMP) of 30 kPa. The water was driven across the membrane initially by evacuation and subsequently by siphonage. A flux of 26 L m^{-2} h^{-1} was obtained with a constant flow valve installed at the permeate outlet. Periodical backwash was applied to delay fouling, combining backwash (60 L m^{-2} h^{-1}, 60 seconds) and air scouring (3 L m^{-2} h^{-1}, 90 seconds). The backwash interval and duration were 3 hours and 2.5 min, respectively. The sludge water in each filtration tank was completely discharged twice a day, with each discharge time taking 0.5 hour. The water recovery rate was approximately 92.3% and the discharged sludge water was about 380 m^3/day for each membrane tank. Moreover, chemical cleaning was carried out twice a month to delay irreversible fouling: the UF membrane was first cleaned with an alkaline solution (0.5% NaOH and 1,000 ppm NaClO) for 6 hours and then cleaned with a 1% citric acid solution for 4 hours.

Experimental protocol

Three experimental scenarios, namely I, II and III, were investigated in comparison with the normal (control) backwash regime, in which backwash, air scouring and sludge water-discharging intervals were 3 hours, 3 hours and 12 hours, respectively. As shown in Table 2, the interval for air scouring was extended to 12 hours in scenario I. In scenarios II and III, the intervals for sludge water discharging and air scouring were increased to 18 hours and 24 hours, respectively. The four experimental scenarios run simultaneously with four UF trains. In each scenario, the UF system was run and monitored for three sludge water discharging cycles. The variations in transmembrane pressure were recorded to assess membrane fouling. Moreover, the turbidity of the mix solutions at different depths (0.2 m, 1.5 m and 2.5 m from the water surface) in the filtration tanks were monitored to evaluate the precipitation of particles. The turbidity was measured by a portable turbidimeter (Hach 2100p, USA). The running costs comprised electricity consumption, self-use water cost and chemical usage during chemical cleaning. The electricity and water prices were US$0.1 per kWh and US$0.03 per m^3, respectively.

To better understand the fouling, the resistance-in-series model was used to describe fouling behavior, as shown in the Equation (1) (Bai et al. 2013).

$$R = \frac{\Delta P}{\mu J} \quad (1)$$

Table 2 | Experiment protocol for optimization of running conditions for the immersed UF system

Parameters	Control	Scenario I	Scenario II	Scenario III
Backwash intervals (h)	3	3	3	3
Air scouring intervals (h)	3	12	18	24
Sludge water discharging intervals (h)	12	12	18	24

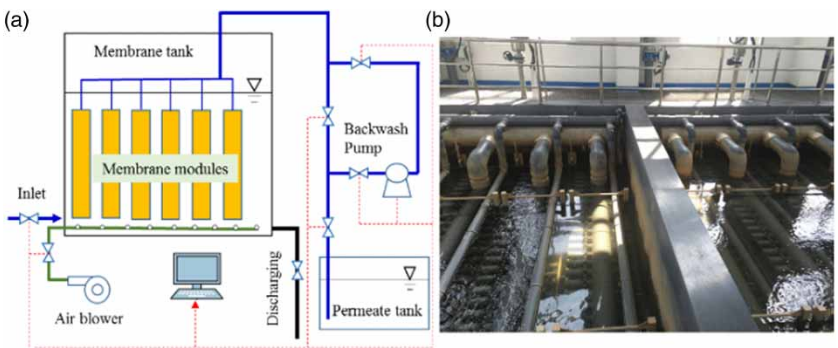

Figure 1 | A schematic diagram (a) and a photograph (b) of the UF system.

where R is the total resistance during the filtration process (m^{-1}), ΔP is the TMP (30 kPa), μ is the dynamic viscosity (Pa s) and J is the membrane flux. The fouling resistance comprises intrinsic membrane resistance, reversible resistance and irreversible resistance. As the experiment duration was quite short, the accumulation of irreversible fouling was insignificant. The monitored fouling resistance could assess development of reversible fouling. To exclude potential impacts of unpredictable factors associated with real systems, the membrane resistances before and after backwash for the whole duration were averaged to give a clearer comparison of the performance of different backwash strategies.

RESULTS AND DISCUSSION

Variation in fouling resistance

Figure 2 shows the profiles of membrane resistances for the UF systems. The membrane resistance generally increased with filtration time and was restored after backwash (Figure 2(a)). With increasing filtration cycles, the membrane resistance increased to some extent. The membrane resistance was greatly delayed when the sludge water was discharged, because the foulants that had accumulated in the UF system were discharged with the sludge water. In scenario I, the membrane resistances in the first 3 hours were lower than those in other scenarios when no cleaning was applied. Because the study was performed in a real water plant, the membrane status could be ideally controlled by a series of factors such as initial membrane status, feed water quality and pumping condition. When the air scouring interval was increased to 12 hours, the membrane resistance did not rapidly increase (Figure 2(b)). This implies that lower backwash intensity did not necessarily result in more severe fouling. When the interval for sludge water discharging was increased to 18 and 24 hours, the membrane resistance did not significantly increase either (Figure 2(c) and 2(d)).

The average resistances before and after backwash in each filtration cycle are summarized and shown in Figure 3. The membrane resistances before and after backwash are associated with total and irreversible fouling, respectively. As shown in Figure 3, the total resistance was

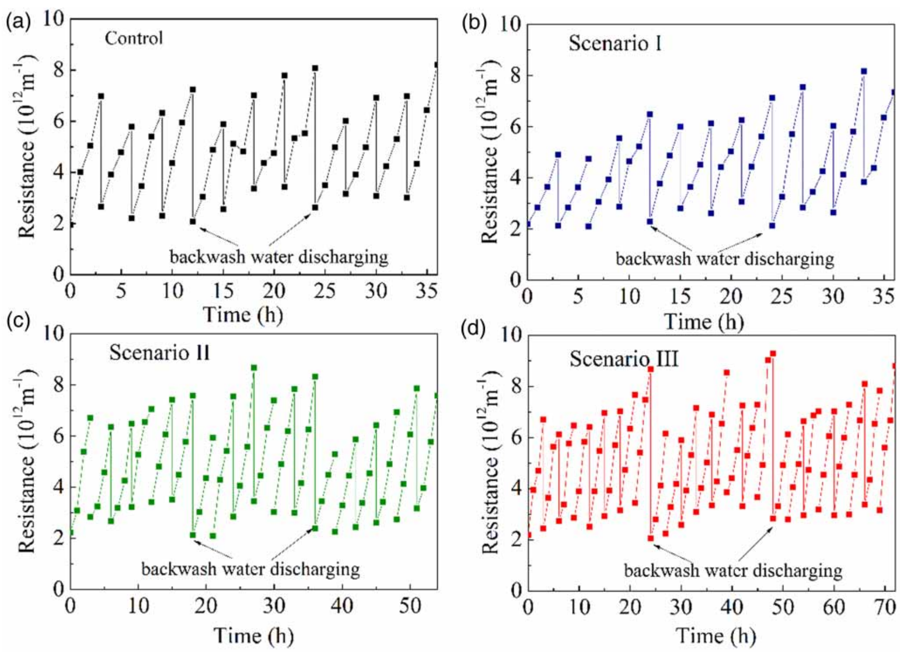

Figure 2 | Profiles of membrane resistance in the three-cycle operation of the immersed UF system with different backwash strategies: (a) control, (b) scenario I, (c) scenario II, and (d) scenario III.

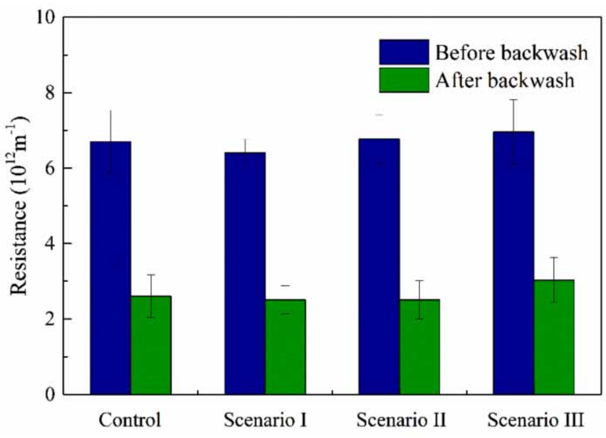

Figure 3 | Effects of reduced air scouring and extended discharge interval of sludge water on fouling.

7.0×10^{12} m^{-1} and the resistance after backwash was 2.6×10^{12} m^{-1} in the control scenario. When the air scouring interval was extended to 12 hours, the resistances before and after backwash did not increase, but decreased to 6.4 and 2.5×10^{12} m^{-1}, respectively. Air-assisted backwash is usually considered to be more effective in fouling alleviation due to stronger surface shear (Remize *et al.* 2010). However, air scouring can destroy the cake layer on the membrane surface, which is regarded a secondary layer to protect the membrane from internal fouling (Cui *et al.* 2017). Hence, the performance of air-assisted backwash in fouling control may be offset. Lok *et al.* (2017) demonstrated that air-assisted backwash resulted in a significantly higher increase in the irreversible fouling resistance for a hollow-fiber UF system. As the intervals for air scouring and sludge water discharging were further increased from 12 hours to 18 hours and 24 hours, both total resistance and irreversible resistance were still not significantly affected (Figure 3), although much more foulant was retained in the UF system due to more water being filtered. This is inconsistent with the general recognition that membrane permeability decreases with more foulants being retained (Kalboussi *et al.* 2018). More understanding on the deposition of foulants is thus warranted in immersed UF systems using low-intensity backwash.

Particle precipitation in multi-cycle filtration

Figure 4 shows variations in the turbidity of the mix solution in a sludge water discharging cycle. The turbidity increased very slowly during filtration because of the retained particles and colloids deposited on the membrane surface. The mix solution turbidity increased sharply after backwash due to

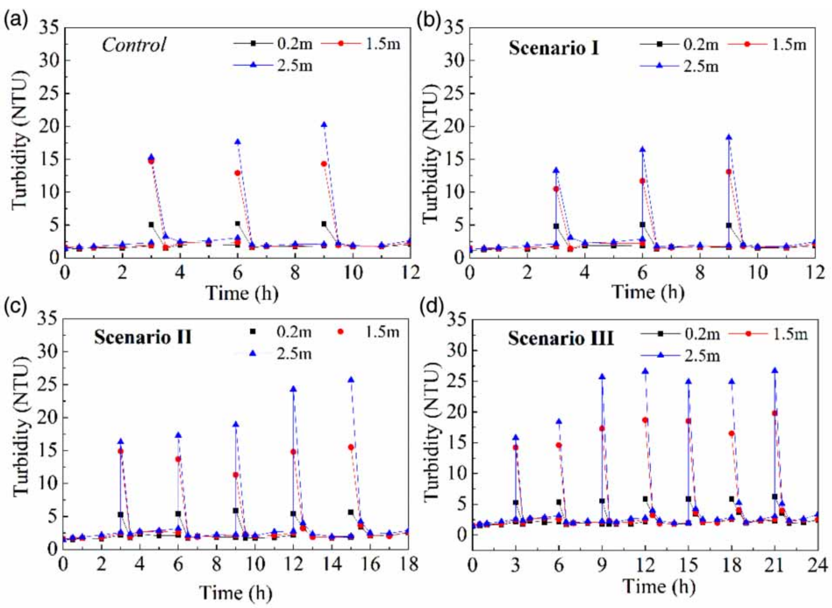

Figure 4 | Variation of turbidity of water in the membrane tank at different water depths: (a) control, (b) scenario I, (c) scenario II, and (d) scenario III. The labels indicate the depths of the turbidity sensors placed in the immersed UF system.

the resuspension of particles and colloids. Subsequently, the mix solution turbidity rapidly decreased because the particles were re-deposited on the membrane surface or precipitated at the bottom of the membrane tank. As the air scouring interval increased to 12 hours (scenario I), the mix solution turbidity after backwash was lower in scenario I than in the control, because fewer particles were resuspended due to less shear being applied. As the sludge water discharging interval increased to 18 hours and 24 hours (scenarios II and III), the mix solution turbidity after backwash apparently increased due to more foulants being retained in the UF system.

The mix solution turbidity before and after backwash is summarized and shown in Figure 5. Generally, the mix solution turbidity increased with water depth due to the precipitation of cake debris. The mix solution turbidity before backwash varied in a low range (1.5–3.5 NTU) because most particles were deposited on the membrane surface during filtration, and parts of large particles precipitated at the bottom of the membrane tank by gravity. The average turbidity substantially increased (5–25 NTU) after backwash due to the resuspension of the particles (Bai *et al.* 2013). Regarding the mix solution turbidity before backwash, the interval extension for air scouring and sludge water discharging played a minor role, regardless of water depth. As shown in Figure 5(b), the mix solution turbidity in the upper area (0.2 m) after backwash did not significantly change with extended intervals for air scouring and sludge water discharging. Generally, the mix solution turbidity after backwashing would decrease if air scouring was not applied, because fewer particles on the membrane surface would be resuspended (De Souza & Basu 2013). However, because the samples were taken 5 min after backwashing, the particles in the upper area might deposit on the membrane surface or precipitate into the lower area, resulting in similar turbidity values in the upper area for different scenarios. The turbidity in the lower areas (1.5 m and 2.5 m) decreased in scenario I and increased in scenarios II and III with the extension of the sludge water discharging interval. The turbidity after backwash was a trade-off between fewer resuspended particles due to lower backwash intensity and more retained particles associated with reduced sludge water discharging. In scenario I, the interval for air scouring was increased to 12 hours, so fewer particles were resuspended from the membrane surface. The increased turbidity in the lower area in scenarios II and III indicated that more particles tended to accumulate at the bottom of membrane tank. However, as shown in Figure 4(c) and 4(d), the turbidity in the lower area tended to remain constant after 12 hours in scenarios II and III. The turbidity in the lower area of membrane tanks was related to resuspension, precipitation and deposition of particles. The resuspension of particles from the membrane surface during backwashing and the precipitation of particles from the upper area could increase the turbidity in the lower area, whereas the deposition of particles to the bottom of the membrane tanks could reduce the turbidity. When the amount of particles getting into the lower area is equal to the amount deposited on the UF tank, the turbidity may not substantially vary.

It is commonly considered that higher backwash intensity is favourable to membrane fouling control (Gu *et al.* 2018). As shown in Figure 5(a), air bubbles may impose a

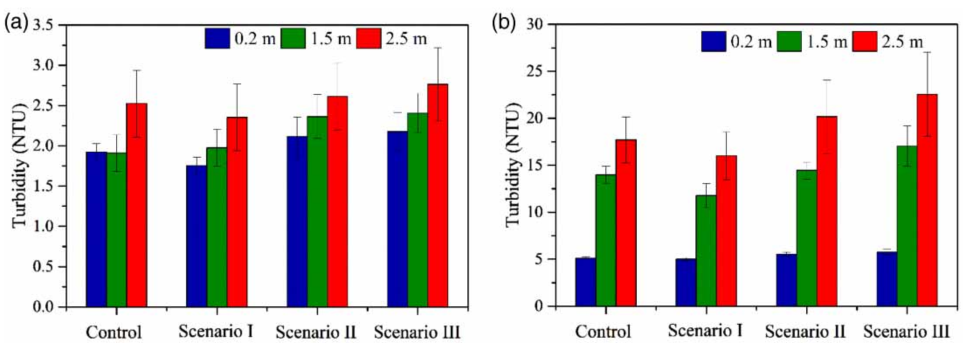

Figure 5 | Effects of reduced physical cleaning intensity of mix solution turbidity at different depths: (a) before backwash and (b) after backwash. The samples were taken from the membrane tank 5 min before and after backwash.

strong shear on the cake layer, enhancing breakage of the cake layer by backwash. In a study on seawater pre-treatment using UF, it was demonstrated that the injection of air during backwash could improve the permeability recovery by 15–39%, depending on the duration of the backwash (Cordier *et al.* 2018). In contrast, the performance of water backwash alone is less efficient in removing the cake layer than air-assisted backwash, with some foulants still adhering to the membrane surface (Figure 6(b)). Hence, the turbidity of the sludge water decreased as the air scouring interval was increased from 3 hours to 12 hours (Figure 5(b)). Moreover, air-assisted backwash can break the cake layer into smaller debris due to the higher energy input, resulting in a greater resuspension of foulants (Massé *et al.* 2015). For an immersed UF system, the sludge water is typically not discharged every time backwash is carried out. In this water plant, the intervals for backwash and sludge water discharging were 3 hours and 12 hours, respectively. The cake debris may re-deposit on the membrane surface in the subsequent filtration, contributing to the increase in fouling resistance (Figure 6(a)) (Qu *et al.* 2015). When only water backwash is applied, the cake debris is larger in size and tends to precipitate at the bottom of the filtration tank. The amount of deposited foulants is thus reduced, positively contributing to fouling control (Bai *et al.* 2013). Although the intervals of air scouring and sludge water discharging were extended, the fouling resistances did not significantly increase (Figure 3). Hence, it is feasible to restrict backwash intensity to reduce the running costs of the UF system without aggravating the membrane fouling.

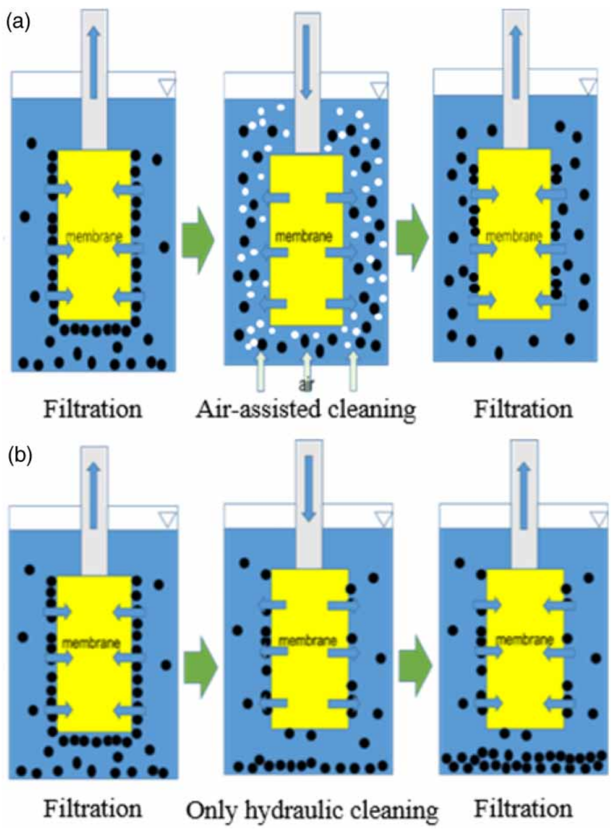

Figure 6 | Schematic diagrams for deposition pathways of particles in the multi-cycle filtration: (a) air-assisted backwash and (b) water backwash alone.

Electricity consumption and running costs

Figure 7 shows the electricity consumption and water production rates of the UF system. When the UF membrane was backwashed by combined water flushing and air scouring at an interval of 3 hours, the electricity demand was 21 kWh 10^{-3} m^{-3} and the water production rate was 92.3%. Because the filtration was driven by gravity, only backwash pumps and air blowers consumed electricity, resulting in a very low electricity consumption (Peter-Varbanets *et al.* 2012).

With the extension of the intervals for air scouring and sludge water discharging, the electricity consumption significantly decreased and the water production rate increased. In contrast, the water production rate was increased by 3% when the intervals for sludge water discharging increased from 12 hours to 24 hours. Table 3 shows the running costs of the UF system, which consisted of electricity costs, water consumption and chemical costs. With the extension of air scouring intervals, the electricity cost slightly decreased. The water cost significantly decreased as the sludge water discharging interval increased from 12 hours to 24 hours. Overall, the running cost for the UF system in this plant was reduced by 16.67% when the intervals of air scouring and sludge water discharging were increased to 24 hours. It should be noted that the capital, maintenance and labor costs were not included.

Implications for management of the immersed hollow-fiber UF system

Because of membrane fouling, backwash is an inevitable step during UF operation, consuming energy and water

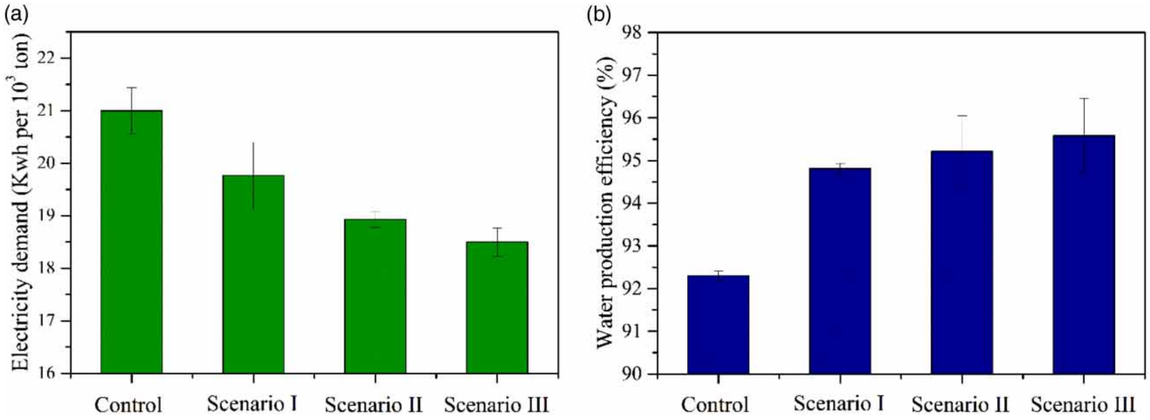

Figure 7 | Effects of reduced physical cleaning intensity on electricity demand (a) and water production efficiency (b).

Table 3 | Running costs of the UF system

Indexes	Control	Scenario I	Scenario II	Scenario III
Electricity cost (US$ 10^{-3} m^{-3})	1.7	1.6	1.5	1.5
Water cost (US$ 10^{-3} m^{-3})	0.7	0.7	0.6	0.4
Chemical cost (US$ 10^{-3} m^{-3})	0.6	0.6	0.6	0.6
Total running cost (US$ 10^{-3} m^{-3})	3.0	2.9	2.7	2.5
Cost saving (%)	0	3.33	10.00	16.67

The price of electricity was set at US$0.1 per kWh. The price of self-use water was US$0.03 per m^3.

(Chang *et al.* 2015). In this work, it was demonstrated that the extension in intervals for air scouring and sludge water discharging did not aggravate membrane fouling but reduced running costs. This is attributed to restricted cake layer breakage associated with reduced backwash intensity (Massé *et al.* 2015; Gan *et al.* 2018). The cake debris preferentially precipitates at the bottom of the membrane tank by gravity, resulting in reduced deposition on the membrane surface. Hence, water backwash only is recommended for the immersed hollow-fiber UF when the sludge water is not discharged. Air scouring is applied with sludge water discharging to maximize exclusion of the retained foulants out of the UF system. However, this work only compared four running scenarios with different intervals for air scouring and backwash discharging, and more efforts should be taken to assess the effects of other parameters, such backwash flux and duration when the proposed backwash strategy is applied. Moreover, more laboratory-scale investigations could be performed to understand the effects of the backwash methods on the migration of colloids and organics in the immersed UF system. It should be noted that the reduced air scouring may cause a risk of clogging, particularly at both ends of the hollow-fiber membrane module.

CONCLUSIONS

In this work, a new backwash strategy, in which the intervals of air scouring and sludge water discharging were extended, was proposed for reducing running costs in the immersed hollow-fiber UF system. The membrane fouling was not aggravated by longer intervals of air scouring and sludge water discharging due to the shift of particle deposition from the membrane surface to the bottom of membrane tank. Moreover, the increase in the sludge water discharging interval from 12 hours to 24 hours increased water the production rate of the UF system by 3%. The running cost of the water plant using gravity-driven UF was reduced by 16.67% as the air scouring and sludge water discharging intervals increased from 3 hours to 24 hours and from 12 hours to 24 hours, respectively.

ACKNOWLEDGEMENT

This work was financially supported by the Natural Science Foundation of China (Grants 51878211, 51708155), Fund from China Postdoctoral Science Foundation (Grants 2016M00251) and Natural Science Foundation of Guangdong province (2019A1515012232). Special thanks to GDH water company for providing the plant for investigation.

REFERENCES

Bai, L., Qu, F., Liang, H., Ma, J., Chang, H., Wang, M. & Li, G. 2013 Membrane fouling during ultrafiltration (UF) of surface water: effects of sludge discharge interval (SDI). *Desalination* **319**, 18–24.

Chang, H., Qu, F., Liu, B., Yu, H., Li, K., Shao, S., Li, G. & Liang, H. 2015 Hydraulic irreversibility of ultrafiltration membrane fouling by humic acid: effects of membrane properties and backwash water composition. *Journal of Membrane Science* **493**, 723–733.

Chang, H., Liang, H., Qu, F., Ma, J., Ren, N. & Li, G. 2016 Towards a better hydraulic cleaning strategy for ultrafiltration membrane fouling by humic acid: effect of backwash water composition. *Journal of Environmental Sciences (China)* **43**, 177–186.

Chang, H., Liang, H., Qu, F., Liu, B., Yu, H., Du, X., Li, G. & Snyder, S. A. 2017 Hydraulic backwashing for low-pressure membranes in drinking water treatment: a review. *Journal of Membrane Science* **540**, 362–380.

Chang, H., Li, T., Liu, B., Vidic, R. D., Elimelech, M. & Crittenden, J. C. 2019 Potential and implemented membrane-based technologies for the treatment and reuse of flowback and produced water from shale gas and oil plays: a review. *Desalination* **455**, 34–57.

Cordier, C., Stavrakakis, C., Sauvade, P., Coelho, F. & Moulin, P. 2018 Air backwash efficiency on organic fouling of UF membranes applied to shellfish hatchery effluents. *Membranes* **8** (3), 48–62.

Cui, Z., Wang, J., Zhang, H. & Jia, H. 2017 Influence of released air on effective backwashing length in dead-end hollow fiber membrane system. *Journal of Membrane Science* **530**, 132–145.

De Souza, N. P. & Basu, O. D. 2013 Comparative analysis of physical cleaning operations for fouling control of hollow fiber membranes in drinking water treatment. *Journal of Membrane Science* **436**, 28–35.

Du, X., Qu, F., Liang, H., Li, K., Chang, H. & Li, G. 2016 Cake properties in ultrafiltration of TiO_2 fine particles combined with HA: in situ measurement of cake thickness by fluid dynamic gauging and CFD calculation of imposed shear stress for cake controlling. *Environmental Science and Pollution Research International* **23** (9), 8806–8818.

Gan, Z., Du, X., Zhu, X., Cheng, X., Li, G. & Liang, H. 2018 Role of organic fouling layer on the rejection of trace organic solutes by nanofiltration: mechanisms and implications. *Environmental Science and Pollution Research* **26**, 33827–33837.

Gu, H., Rahardianto, A., Gao, L. X., Caro, X. P., Giralt, J., Rallo, R., Christofides, P. D. & Cohen, Y. 2018 Fouling indicators for field monitoring the effectiveness of operational strategies of ultrafiltration as pretreatment for seawater desalination. *Desalination* **431**, 86–99.

Jacangelo, J. G., Trussell, R. R. & Watson, M. 1997 Role of membrane technology in drinking water treatment in the United States. *Desalination* **113**, 119–127.

Kalboussi, N., Harmand, J., Rapaport, A., Bayen, T., Ellouze, F. & Ben Amar, N. 2018 Optimal control of physical backwash strategy – towards the enhancement of membrane filtration process performance. *Journal of Membrane Science* **545**, 38–48.

Li, S., Heijman, S. G. J., Verberk, J. Q. J. C., Verliefde, A. R. D., Kemperman, A. J. B., van Dijk, J. C. & Amy, G. 2009 Impact of backwash water composition on ultrafiltration fouling control. *Journal of Membrane Science* **344** (1–2), 17–25.

Li, S., Heijman, S. G. J. & van Dijk, J. C. 2010 A pilot-scale study of backwashing ultrafiltration membrane with demineralized water. *Journal of Water Supply: Research and Technology – AQUA* **59** (2–3), 128.

Li, K., Wen, G., Li, S., Chang, H., Shao, S., Huang, T., Li, G. & Liang, H. 2019 Effect of pre-oxidation on low pressure membrane (LPM) for water and wastewater treatment: a review. *Chemosphere* **231**, 287–300.

Lok, A., Wray, H., Bérubé, P. & Andrews, R. C. 2017 Optimization of air sparging and in-line coagulation for ultrafiltration fouling control. *Separation and Purification Technology* **188**, 60–66.

Massé, A., Arab, O., Séchet, V., Jaouen, P., Pontié, M., Sabiri, N.-E. & Plantier, S. 2015 Performances of dead-end ultrafiltration of seawater: from the filtration and backwash efficiencies to the membrane fouling mechanisms. *Separation and Purification Technology* **156**, 512–521.

Miyoshi, T., Setiadi, T., Effendi, A. J., Maeda, H., Tsukaraha, T., Yi, H., Jun, H., Saito, M. & Matsuyama, H. 2016 Low-cost water treatment system using submerged membrane filtration in developing countries. *Desalination and Water Treatment* **57** (39), 18101–18108.

Peter-Varbanets, M., Gujer, W. & Pronk, W. 2012 Intermittent operation of ultra-low pressure ultrafiltration for decentralized drinking water treatment. *Water Research* **46** (10), 3272–3282.

Qu, F., Du, X., Liu, B., He, J., Ren, N., Li, G. & Liang, H. 2015 Control of ultrafiltration membrane fouling caused by Microcystis cells with permanganate preoxidation: significance of in situ formed manganese dioxide. *Chemical Engineering Journal* **279**, 56–65.

Remize, P. J., Guigui, C. & Cabassud, C. 2010 Evaluation of backwash efficiency, definition of remaining fouling and characterisation of its contribution in irreversible fouling: case of drinking water production by air-assisted ultra-filtration. *Journal of Membrane Science* **355** (1–2), 104–111.

Van Der Bruggen, B., Van Decasteele, C., Van Gestel, T., Doyen, W. & Leysen, R. 2003 A review of pressure-driven membrane processes in wastewater treatment and drinking water production. *Environmental Progress* **22**, 11.

Ye, Y., Sim, L. N., Herulah, B., Chen, V. & Fane, A. G. 2010 Effects of operating conditions on submerged hollow fibre membrane systems used as pre-treatment for seawater reverse osmosis. *Journal of Membrane Science* **365** (1–2), 78–88.

Ye, Y., Chen, V. & Le-Clech, P. 2011 Evolution of fouling deposition and removal on hollow fibre membrane during filtration with periodical backwash. *Desalination* **283**, 198–205.

Zhang, X., Fan, L. & Roddick, F. A. 2015 Effect of feedwater pre-treatment using UV/H_2O_2 for mitigating the fouling of a ceramic MF membrane caused by soluble algal organic matter. *Journal of Membrane Science* **493**, 683–689.

First received 30 October 2019; accepted in revised form 27 March 2020. Available online 15 April 2020