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Analysis of the biodegradation performance and biofouling in a halophilic MBBR-MBR to improve the treatment of disinfected saline wastewater

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HIGHLIGHTS
• The NaClO-containing wastewaters were treated in a saline MBBR-MBR system.
• The synergistic toxicity from NaClO and NaCl was observed to the microorganisms.
• The behaviour of biofoulants showed the levels of fouling and biodegradability.
• A novel strategy of biofoulants monitoring was proposed for membrane antifouling.

G R A P H I C A L  A B S T R A C T

A B S T R A C T

Disinfectant-containing wastewaters have been generated from many places, including marine industries. The synthetic NaClO-containing wastewaters have been effectively treated in a saline MBBR-MBR (moving bed biofilm reactor & membrane bioreactor) system containing marine microorganisms. A low concentration of NaCl (below 100 mg/L) is not enough to kill the microorganisms, but can affect their bioactivity and induce membrane biofouling. A linear relationship has been obtained for the half-life of membrane biofouling as a function of the NaClO concentration (10–100 mg/L): [half-life] = 25 –0.12 × [NaClO concentration]. The COD and NH3--N removals are the highest at a salinity of 30 g/L for the marine bioreactors. The behaviour of the typical biofoulants, measured real-time by fluorescence spectroscopy, can indicate the levels of membrane biofouling and microbial activity, responding to the NaClO and NaCl influences. Based on the behaviour of biofoulants, this work has also proposed a novel strategy of biofoulants monitoring for membrane antifouling, where antifouling responses can be carried out when the concentration of biofoulants significantly increases.

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1. Introduction

Due to the global spread of 2019 novel coronavirus (2019-nCoV), concentrated NaClO solution (from various disinfectants) has been largely and frequently used in various places. U.S. CDC (Centers for
Disease Control and Prevention) has recommended diluted household bleach solutions, containing at least 1000 mg/L NaClO, for surface disinfection against the coronaviruses (CDC, 2020). The disinfectant has been sprayed by sanitation trucks in China, generating atomized NaClO solution of ~500 mg/L for disinfection on city streets and in the air (EconomicDaily, 2020). Since Wang et al. (2005) has reported that SARS coronavirus existed in hospital sewage, such sewages may contain 2019-nCoV and require deep disinfection. In hospitals and stockbreeding industries, faecal wastes are suggested to be disinfected using NaClO generators with 10,000–20,000 mg/L available chlorine (China SAo, 2011). Other industries would also use concentrated NaClO for disinfection against the coronaviruses. The above situations result in high concentrations of NaClO in sewages and industrial wastewaters. Although NaClO is unstable, a low concentration of 2 mg/L of NaClO can lead to bacterial lysis and changes in MLSS (mixed liquor suspended solid) concentration (Cai and Liu, 2016). The changes in performance of bioreactors against high concentrations of NaClO thus require to be studied.

A membrane bioreactor (MBR) consists of an activated-sludge unit and a membrane separation unit. MBR is a smart option for water treatment, as studied and reviewed by Ngo’s group (Cheng et al., 2018; Khan et al., 2018; Yu et al., 2018), showing efficient wastewater treatment, small space requirement, effective solid-liquid separation, and many other advantages. The performance of MBR largely relies on the behaviour of microorganisms, where there is a tendency of decreased biodegradability and increased biofouling upon environmental shocks (Tan et al., 2017b). Biomolecules from bacterial secretion and lysis lead to physical blocking of membrane pores, adsorption of bacteria cells and formation of sludge cakes on the membrane (Statz et al., 2008; Li et al., 2016). Some of the biomolecules, including extracellular polymeric substances (EPS) and soluble microbial products (SMP), which are dissolvable or dispersible, may diffuse deeply into the membrane pores resulting in severe biofouling (Kunacheva and Stuckey, 2014). EPS and SMP are key biofoulants that require to be monitored for membrane antifouling.

Because of a low stability of NaClO, the concentration of NaClO can significantly change in disinfected wastewaters, especially for those relative to marine industries (i.e. seafood factories, wharf places). The environmental shocks from changes in NaClO concentration can cause abnormal bacterial secretion and lysis in MBR, increasing the concentrations of the membrane biofoulants (EPS and SMP). Antifouling strategies have been focused on the modification of MBR systems for decreased concentrations of these biofoulants (Lin et al., 2014; Deng et al., 2015). Moreover, MBR can be integrated with other highly-bioactive reactors for improved biodegradation efficiency as an alternative antifouling strategy, where large biofoulants are degraded to be smaller molecules with less biofouling tendency (Tan and Li, 2016). Following the above antifouling strategies, however, a proper monitoring system is required to warn us about any biofouling situations in MBR for timely antifouling responses (Flemming, 2003). Transmembrane pressure (TMP), read from a pressure gauge, has been widely used as an indicator in practice for real-time monitoring, where a high TMP over 52 kPa means a significant membrane fouling (Li et al., 2007). However, the increase of TMP lags behind the changes in bacterial behaviour and concentrations of the biofoulants. Other methods, such as microscopic observation (McCoy et al., 1981), FTIR spectroscopy (Thygesen et al., 2014) and fluorescence spectroscopy (Yu et al., 2015), have been used as effective methods to analyze the changes in biofoulants.

Saline organic wastewater is an emerging challenge for MBR technique, especially when toxic component (i.e. phenol) exists, requiring designs of novel membranes and MBR systems (Ren et al., 2020). As reported by Tan et al. (2019), physical, chemical and biological techniques have been used over the years to treat saline wastewaters, including mechanical vapor compression, membrane distillation and forward osmosis technologies (Shaffer et al., 2013), UV/persulfate-based saline wastewater treatment (Yuan et al., 2014), bioelectrochemical systems (Kim and Logan, 2013), and so forth. Compared to the physico-chemical methods, biological techniques are relatively cheap in operation. Conventional MBR can be used for low-saline wastewater treatments, whereas MBBR-hybrid systems can be used for high-saline wastewater treatments with reduced membrane fouling and improved biodegradability (Tan et al., 2019). The typical bioreactors for MBR integration include MBBR (moving bed biofilm reactors), BCOR (biological contact oxidation reactor), UASB (up-flow anaerobic sludge blanket), SBR (sequencing batch reactor), MFC (microbial fuel cells), chemostat and bio-carriers. Since MBBR has unique advantages of fast start-up, large biomass, direct dosing and space saving, MBBR-MBR has been used in this work for saline wastewater treatment, where the key strategy involves the integration of another bioreactor and the use of highly salt-tolerant microorganisms (Nguyen et al., 2018). The NaClO-containing wastewater, as introduced above, is an emerging wastewater from disinfection against the coronaviruses. To the best of our knowledge, the effect of NaClO on membrane biofouling has not been studied for saline wastewater treatment in MBR systems. The oxidation/disinfection of NaClO and the osmotic pressure from high salinity would have synergistic detrimental effect to microorganisms in bioreactors. In this work, for the treatment of NaClO-containing saline wastewater, a strategy has been used by the integration of MBR with MBBR (moving bed biofilm reactors) and the use of marine microorganisms. As reported by The World Organisation for Animal Health (OIE) (2009), 50 mg/L chlorine is recommended for complete disinfection of effluent water in aquaculture, although higher concentrations may be used under certain conditions. Due to the worldwide spread of coronavirus, more disinfectant has been used than usual in many places, including marine industries. Thus, concentrations of 0–100 mg/L have been used in this work for a relatively comprehensive study. The behaviour of typical biofoulants has been measured as a function of membrane biofouling, following a real-time monitoring technique (Tan et al., 2017b) where the fulvic acid-like and humic acid-like molecules have higher biofouling tendency than the soluble microbial by-product-like molecules. When a quick response is performed after environmental shocks, the membrane biofouling is minimized in the saline MBBR-MBR. The findings from this study may provide a method to monitor and reduce membrane biofouling for saline MBR systems in toxic environments.

![Schematic diagram of the saline MBBR-MBR (moving bed biofilm reactor & membrane bioreactor) system.](image-url)
2. Materials and methods

2.1. Preparation of the saline MBBR-MBR system

Fig. 1 shows the lab-scale MBBR-MBR (moving bed biofilm reactor & membrane bioreactor) system for saline wastewater treatment. Both the MBBR and the MBR had an effective volume of 10 L in separated compartments (300 mm × 250 mm × 170 mm). The MBBR was added with three hundreds of biofilm carriers, where each carrier has a size of 14.5 mm × 14.5 mm × 8.2 mm and a surface area of 650 m²/m³ (Biowater Technology AS, Norway). The MBR had a membrane module of 250 m × 200 mm × 50 mm using polypropylene membranes for filtration. The membrane pores had a diameter of 0.03 µm and the filtration area was 0.2 m². During operation, the synthetic wastewater was pumped to the MBBR with a flux of 5 L/m²/h. Part of the fluid from the MBR, namely backflow, was pumped back to the MBBR with a flux of 5 L/m²/h. Thus the flux was 10 L/m²/h from MBBR to MBR. The effluent was collected after the MBR filtration with a membrane flux of 5 L/m²/h. The dissolved oxygen (DO) was 2.5 mg/L and the fluid temperature was controlled at 20 °C in the MBBR-MBR system. The parameters were the same as the parameters for cultivation of marine activated sludge (Tan et al., 2017a).

The MBBR-MBR system was dosed with a marine activated sludge for saline wastewater treatment. The marine activated sludge contained abundant salt-tolerant microorganisms originally from the sea, as reported in our previous report (Tan et al., 2017a). Typically, the marine activated sludge was cultivated in seawater using sea mud as seed in an aerobic bioreactor for at least 40 days until its SVI (sludge volume index) stably exceeds 70 mL/g. The marine activated sludge was used to seed the MBBR-MBR system. The parameters were the same as the parameters for the MBBR-MBR system. The effective operation time of the MBBR was more than one month for the control group. For the group with a high NaClO concentration of 25 mg/L, the effective operation time decreased to 20 days where the concentration of NaCl was 30,000 mg/L in the MBBR-MBR system. The effect of NaClO concentration on membrane biofouling was studied by monitoring the TMP (kPa) as a function of operating time (days), at an optimal salinity of 3.2%. Since the change in salinity (osmotic pressure) may have a synergistic detrimental effect alongside NaClO to the microorganisms, the concentration of NaCl was changed from 15,000 to 40,000 mg/L, meanwhile the concentration of NaClO was changed from 0 to 100 mg/L for the saline wastewater treatment. The COD removal was measured by a potassium permanganate method and the NH₄-N removal was measured by spectrophotometry, according to the standard methods (Chinese-SEPA, 1997). The behaviour of the typical biofoulants were measured using a Hitachi F-2700 Fluorescence Spectrophotometer (Hitachi Ltd., Japan), in order to reveal the detrimental effect from NaClO and NaCl on the microorganisms. Instead of the EEM (excitation-emission matrix) scanning, a simple-read mode was used at (λex/λem) 350nm/430 nm, 260nm/445 nm, 275nm/325 nm and 230nm/290 nm, respectively, for the detection of the concentrations of fulvic acid-like molecules, humic acid-like molecules and soluble microbial by-product-like molecules, which were the typical biofoulants from bacterial secretion and lysis. Three replicate analyses were done and the results were presented as means ± STD (standard deviation). The background concentrations of NaClO, COD and NH₄-N were 0, 10 ± 5 mg/L, 0.5 ± 0.3 mg/L for the bioreactors before the wastewater treatment. The background COD and NH₄-N can significantly affect the results.

2.2. NaClO-containing saline wastewater treatment

The composition of the synthetic wastewaters used in this work is shown in Table 1. The NaClO household disinfectant (Xiangya, China) was purchased from the market. All other chemicals are analytical reagents (AR) that the potato starch is purchased from Tianjin Kermel Chemical Reagent Co., Ltd., China and other chemicals are from Tianjin Kermel Chemical Reagent Co., Ltd., China.

The concentration of NaClO varied from 0 to 100 mg/L giving oxidation/disinfection stress to the marine microorganisms in the MBBR-MBR system. The effect of NaClO concentration on membrane biofouling was studied by monitoring the TMP (kPa) as a function of operating time (days), at an optimal salinity of 3.2%. Since the change in salinity (osmotic pressure) may have a synergistic detrimental effect alongside NaClO to the microorganisms, the concentration of NaCl was changed from 15,000 to 40,000 mg/L, meanwhile the concentration of NaClO was changed from 0 to 100 mg/L for the saline wastewater treatment. The COD removal was measured by a potassium permanganate method and the NH₄-N removal was measured by spectrophotometry, according to the standard methods (Chinese-SEPA, 1997). The behaviour of the typical biofoulants were measured using a Hitachi F-2700 Fluorescence Spectrophotometer (Hitachi Ltd., Japan), in order to reveal the detrimental effect from NaClO and NaCl on the microorganisms. Instead of the EEM (excitation-emission matrix) scanning, a simple-read mode was used at (λex/λem) 350nm/430 nm, 260nm/445 nm, 275nm/325 nm and 230nm/290 nm, respectively, for the detection of the concentrations of fulvic acid-like molecules, humic acid-like molecules and soluble microbial by-product-like molecules, which were the typical biofoulants from bacterial secretion and lysis. Three replicate analyses were done and the results were presented as means ± STD (standard deviation). The background concentrations of NaClO, COD and NH₄-N were 0, 10 ± 5 mg/L, 0.5 ± 0.3 mg/L for the bioreactors before the wastewater treatment. The background COD and NH₄-N can significantly affect the results.

2.3. Anti-fouling method for environmental shocks

In a typical study of 28 days, the concentration of NaClO was 5 mg/L and the concentration of NaCl was 30,000 mg/L in the synthetic wastewaters. An increase of the NaClO concentration from 5 to 50 mg/L was applied to the system at the 10th day. A decrease of the NaCl concentration from 30,000 to 20,000 mg/L was applied to the system at the 20th day. The TMP and the spectroscopic intensities of the fulvic acid-like molecules, humic acid-like molecules and soluble microbial by-product-like molecules were monitored. For the control group, an antifouling response would only be performed if the TMP significantly increased. For the experimental group, antifouling responses, namely removing any environmental shocks, were carried out when the sum of the spectroscopic intensities of the typical biofoulants significantly increased.

3. Results and discussion

3.1. The effect of NaClO on the MBR performance

Fig. 2a shows the change in TMP (related to membrane biofouling) as a function of operating time at different NaClO concentrations of 0–100 mg/L. Responding to the released biofoulants from bacterial secretion and lysis, the TMP gradually increased due to the accumulation of biofoulants on membrane surface and in membrane pores causing a lower membrane permeability (van Nieuwenhuijzen et al., 2008). The tendency of membrane biofouling at a low NaClO concentration of 5 mg/L was not significantly different compared with the control group (no NaClO added). At higher NaClO concentrations, the tendency of membrane biofouling rose with increasing the NaClO concentration. The effective operation time of the MBR was more than one month for the control group. For the group with a high NaClO concentration of 100 mg/L, the effective operation time decreased to 20 days where the TMP nearly reached the critical fouling pressure of 52 kPa with a low membrane permeability (Liang et al., 2007). To better compare these fouling profiles with different NaClO concentrations, the half-life of membrane biofouling, when the TMP reached 26 kPa (half of the critical fouling pressure), was plotted as a function of
the NaClO concentration. As shown in Fig. 2b, the saline MBBR-MBR was not sensitive to NaClO with low concentrations under 5 mg/L. Interestingly, a linear relationship was noticed for the half-life of membrane biofouling as a function of the NaClO concentration ranging from 10 to 100 mg/L. After the linear fitting by Origin software, the following equation has been given: 

\[ y = 25 - 0.12x, \]

where \( y \) is the half-life and \( x \) is the NaClO concentration; \( R^2 = 0.9990 \).

Since the oxidation/disinfection of NaClO and the osmotic pressure from salinity changes have synergistic detrimental effect to the microbes in the saline MBBR-MBR, the effects of NaClO and NaCl concentrations have been studied on the bacterial biodegradation. Fig. 3 show the COD and NH\(_3\)-N removals at different concentrations of NaClO (0–100 mg/L) and NaCl (15–40 g/L). Since the marine activated sludge was cultivated in seawater, the COD and NH\(_3\)-N removals (around 98% and 52%, respectively) were the highest at the NaCl concentration of 30 g/L and the NaClO of 0. The decreasing trends of the COD (Fig. 3a) and NH\(_3\)-N (Fig. 3b) removals as a function of NaClO concentration for all groups overall agreed well with the decreasing trend of the biofouling half-life (Fig. 2b), meaning that the biodegradability (namely the bioactivity) was the key factor affecting the membrane biofouling. The lowest COD and NH\(_3\)-N removals (around 47% and 21%, respectively) were observed at the NaCl concentration of 15 g/L and the NaClO of 100 mg/L. The difference between the lowest and the highest COD removal (47%–98% = −51%), however, was larger than the sum of the differences of COD removal for NaClO influence only (−25%) and NaCl influence exclusively (−12%). The difference between the lowest and the highest NH\(_3\)-N removal (21–52% = −31%) was also larger than the sum of the differences of NH\(_3\)-N removal for NaClO influence only (−13%) and NaCl influence exclusively (−7%). The above results suggest the synergistic detrimental effect from NaClO and NaCl.

### 3.2. Behaviour of the typical membrane biofoulants

The effect of NaClO on the MBR performance was mainly related to the behaviour of the typical biofoulants from bacterial secretion and lysis. On one hand, the toxins increased the number of dead microorganisms (autolysis) and the tendency of bacterial secretion for extracellular biodegradation or cell protection, releasing more EPS and SMP (Reid et al., 2006b; Kokabiana et al., 2013). These EPS and SMP may play a key role in inducing a membrane biofouling (Hamoda and Alattar, 1995). On the other hand, the toxins lowered the bioactivity of the microorganisms, where some large biofoulants could not be biodegraded to be small molecules with less biofouling influence (Tan and Li, 2016). The concentrations of the typical biofoulants, therefore, can indicate and predict the situations of membrane biofouling, responding to any environmental shocks (Al-Halbouni et al., 2008; Fallah et al., 2010; Gaoa et al., 2010; Wang et al., 2010).

Fig. 4 show the change in fluorescent intensities of the typical biofoulants as functions of NaClO and NaCl concentrations. The concentrations of the biofouling-related EPS and SMP were measured by the sums of the fluorescent intensities of the typical biofoulants, including fulvic acid-like molecules, humic acid-like
molecules and soluble microbial by-product-like molecules. At the optimal conditions when the concentration of NaClO was 0 and the concentration of NaCl was 30 g/L, the sum of the intensities (concentrations) of the typical biofoulants was the lowest, indicating a favoured environment for the marine microorganisms. At a slight increased concentration of NaClO of 5 mg/L, the concentrations of the biofoulants did not significantly change, agreeing with the above results studying the changes in TMP (Fig. 2) and biodegradation (Fig. 3). At the NaCl concentration of 30 g/L, when the concentration of NaClO further increased from 10 to 100 mg/L the sum of the biofoulants intensities (concentrations) increased from 3500 to 5100 cps. The result suggested that the marine microorganisms were only sensitive to NaClO with concentrations higher than 5 mg/L. As reported by Cai and Liu (2016), however, the conventional (non-marine) microorganisms in MBR were sensitive to NaClO of 2 mg/L showing some bacterial lysis of ~10%. It is suggested that the marine microorganisms may have higher tolerance to NaClO than the non-halophilic microorganisms in MBR, possibly due to a similar protection mechanism against high salinities for these salt-tolerant bacteria (Tan et al., 2019). In saline environments, microorganisms release extracellular biomolecules (EPS and SMP) to build a diffusion barrier between the cell wall and extreme environments (Meng et al., 2016). In our previous report, the marine microorganisms also have a high tolerance to phenolic environments possibly due to the barrier of extracellular biomolecules (Tan et al., 2017a). The barrier possibly contributes to the NaClO tolerance of 5 mg/L for marine microorganisms. Moreover, the intensity of soluble microbial by-product-like molecules (in blue colour, Fig. 4d) increased relatively faster than the intensities of fulvic acid-like (in red colour) and humic acid-like (in green colour) molecules, with increasing the NaClO concentration from 5 to 20 mg/L. With further increasing the NaClO concentration from 20 to 100 mg/L, however, the intensity of soluble microbial by-product-like molecules slightly decreased whereas the intensities of fulvic acid-like and humic acid-like molecules significantly increased. It was suggested that the functioning biodegradation at the relatively low NaClO concentrations of 5–20 mg/L converted the fulvic acid-like and humic acid-like molecules to be the soluble microbial by-product-like molecules, which were smaller and have less biofouling ability, or even inorganic molecules (i.e. water and CO2). At the high NaClO concentration of 100 mg/L, the intensities for the three types of biofoulants were similar. This kind of situations were also observed for other groups at different NaCl concentrations.
The intensities (concentrations) of the biofoulants were affected by the synergistic detrimental effect from NaClO and NaCl. As reported by Cai and Liu (2016), bacterial lysis can be caused by NaClO disinfection at concentrations over 2 mg/L. Even at low levels, the NaClO oxidation damages extracellular biomolecules, reduces bioactivity and possibly affect sludge characteristics. On the other hand, the osmotic pressure from NaCl results in bacteria aggregation, acceleration of endogenous respiration, release of more biomolecules through secretion and autolysis of cells (Kincanno and Gaudy, 1968; Hamoda and Alattar, 1995; Reid et al., 2006a). In order to reduce the NaCl toxicity, microorganisms generate extracellular biomolecules, adjusting the extracellular microenvironment and acting as a diffusion barrier between the cell wall and extreme environments (Meng et al., 2016). If the extracellular biomolecules are affected by NaClO oxidation, the NaCl tolerance of microorganisms may significantly decrease. Therefore, Fig. 4c shows a similar trend of intensity changes compared with Fig. 4e. Fig. 4b is also similar to Fig. 4f, however at the highest NaClO concentration of 100 mg/L, the intensity of soluble microbial by-product-like molecules is relatively higher than the intensities of fulvic acid-like and humic acid-like molecules at the NaCl concentration of 40 g/L (Fig. 4f) compared to the group at the NaCl concentration of 20 g/L (Fig. 4b). The result again suggests that the marine microorganisms may show higher tolerance to NaClO at saline environments. With the largest difference of NaCl concentration, Fig. 4a shows the highest concentrations of the biofoulants, agreeing with the highest membrane biofouling tendency (Fig. 2) and the lowest biodegradation rate (Fig. 3). Overall, the behaviour of the typical biofoulants, measured real-time by fluorescence spectroscopy, can indicate the levels of membrane biofouling and microbial activity, responding to the NaClO and NaCl influences.

3.3. Comparison of TMP monitoring and biofoulants monitoring

Based on the spectroscopic monitoring, the intensity (concentration) of the typical biofoulants showed the real-time level of membrane biofouling. The conventional monitoring method was also performed by recording the TMP to evaluate the level of membrane biofouling. As a conventional strategy of TMP monitoring for membrane antifouling, antifouling responses could be carried out when the TMP significantly increased. As shown in Fig. 5a, the TMP gradually increased so that no responses of antifouling were required to perform when the conventional strategy was used. On the 28th day, the membrane was considered as fouling when the TMP exceeded 52 kPa with a low membrane permeability (Liang et al., 2007). The fouled membrane in the MBR was then cleaned for reuse. From the spectroscopic monitoring of biofoulant intensity, however, there were dramatic increases in the concentrations of biofoulants at the 10th day and the 20th day responding to the changes in the concentrations of NaClO and NaCl, respectively, as shown in Fig. 5a. As a novel strategy of biofoulants monitoring for membrane antifouling, antifouling responses could be carried out when the detected fluorescent intensity significantly increased. As shown in Fig. 5b, the intensity of biofoulants significantly increased at the 10th day and the 20th day responding to the environmental shocks. As soon as the warnings observed, the NaClO and NaCl shocks were removed for antifouling when the novel strategy was used. Subsequently, the intensity of biofoulants gradually decreased. The TMP then had a slower raising rate, showing a smaller tendency of membrane fouling. The antifouling response was carried out when the intensity of biofoulants suddenly increased. The recovery of bioactivity of bioreactors took about 2 days (from 10th day to 14th day; from 20th day to 24th day). Overall, using the novel strategy of biofoulants monitoring the membrane biofouling rate was approximately half of the rate when the conventional strategy of TMP monitoring was used. It is suggested that the spectroscopic monitoring of membrane biofoulants has anti-biofouling advantage in the saline MBBR-MBR system for the NaClO-containing wastewater treatment.

4. Conclusions

The NaClO-containing saline wastewaters were effectively treated. The MBR was not sensitive to low NaClO concentrations under 5 mg/L. A linear relationship was noticed for the half-life of membrane biofouling as a function of the NaClO concentration. The synergistic detrimental effect from NaClO and NaCl was found to be higher than their toxicities simply acting alone. The behaviour of the typical biofoulants, measured real-time by fluorescence spectroscopy, indicated the levels of membrane biofouling and microbial activity, responding to the NaClO and NaCl influences. This work also proposed a novel strategy of biofoulants monitoring for the membrane anti-biofouling.

Credit author statement

Mengchang Xu: Methodology, Investigation, Writing - original draft. Wenhu Zhou: Formal analysis, Investigation, Supervision. Xuncai Chen: Investigation. Ying Zhou: Data curation. Binsheng He: Investigation. Songwen Tan: Supervision, Writing - Review & Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.
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