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Evaluating the effect of aeration rate on quorum quenching membrane bioreactors: Performance of activated sludge, membrane fouling behavior, and the energy consumption analysis

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ABSTRACT

Microbial quorum quenching (QQ) has recently been proven to be an efficient approach to mitigate biofouling in membrane bioreactors (MBRs). It can reduce biopolymers production and improve sludge conditions. Also, aeration intensity is considered to be directly interconnected with membrane fouling. In this study, the impact of aeration rate on the performance, membrane fouling, and the energy consumption of quorum quenching membrane bioreactor (QQ-MBR) and conventional membrane bioreactor (C-MBR) were exposed. We investigated the synergistic effects of aeration intensity and QQ on membrane fouling control in MBRs and analyzed the energy consumption of reactors under different conditions. QQ was found to mitigate biofouling significantly, but the membrane fouling mitigation efficiency was lowest (only 17.9 %) at high aeration intensity. Moreover, QQ reduced the content of SMP and EPS in sludge (over 20 % decreasing), and a better QQ performance was observed at middle aeration intensity. As for energy consumption, the most energy was consumed at high aeration intensity. QQ can minimize the aeration intensity required for the regular operation of MBR, thereby optimizing the energy consumption.

1. Introduction

Membrane bioreactor (MBR) has been widely concerned and applied in recent years because of its superiority compared with traditional activated sludge processes [1], such as superior effluent quality, lower sludge production, reduced footprint and higher volumetric loading (Huang et al., 2019; [2,3]). However, membrane fouling, mainly biofouling, has affected impacts membrane filtration and the lifespan of membrane modules seriously. In addition, biofouling has triggered more frequent membrane module cleaning (physical or chemical) and replacement, and also increased energy demands and lower sewage treatment performance, which finally dramatically increased the operating costs of MBRs [4,5].

Biofouling is considered unfavorable microorganisms accumulation, which primarily results from bacteria attaching to membrane surface as well as biofilm growing [6,7]. This becomes a bottleneck limiting the development of membrane treatments, especially MBRs ([8]; Shi et al., 2021). Therefore, many physical or chemical methods have been developed and applied to mitigate biofouling, such as tangential scouring on the surface, backwashing, regulating aeration, intermittent suction and adding exogenous anti-bacterial medicine [9,10]. Also, it has been proven to get good efficacy in extending the operating time of MBRs. However, these methods cannot fundamentally avoid biofilm formation because it is a natural process of microorganisms growing on the membrane surface. With the development of sewage treatment technology, the strategy of intercellular communication in sludge systems provided a way of thinking about biofouling. Small-molecule chemicals (autoinducers) can regulate the density-dependent cell-cell communication between bacteria, which is called quorum sensing (QS) [11,12]. QQ refers to the process of autoinducer-based QS that can be

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interfered with or interrupted, and then inhibits bacterial gene expression, thereby preventing biofilm formation [13,14]. QQ-based technology (porcine kidney acylase I) was applied in MBRs and showed excellent mitigation in membrane biofouling. Since then, this biofouling control technology based on QQ has gained increasing attention and has been researched more frequently [8,15].

QQ enzymes entrapped with sodium alginate capsules were applied to control biofouling in an MBR [16]. Then, Weerasekara et al. [17] immobilized QQ bacteria in a microbial vessel instead of QQ enzymes. In these studies, membrane biofouling was significantly mitigated without any negative influence on the efficiency of operations. It was reported that QQ (enzymes/bacteria) could change the characteristics of activated sludge, such as sludge settleability and viscosity, the size of microbial flocs, zeta potential of sludge and the structure of EPS. Maqbool et al. [18] also claimed that cell entrapping beads of QQ could improve filtration properties and sludge dewaterability. The effects of QQ on activated sludge systems cannot be ignored. Besides, aeration intensity, acting as one of the significant operation conditions in MBRs, directly determined dissolved oxygen (DO) concentration in the mixed liquor, which was also essential for microbial growth. Thus, the aeration intensity is also a critical factor affecting sludge performance, scouring effect, QQ bacteria growth, and directly determining the energy consumption of the devices. However, most of the previous studies only analyzed the impact of QQ on activated sludge [19,20]. It was reported the performance of activated sludge was changed at high aeration intensity in QQ-MBRs due to the scouring effect [21]. In order to explore the experimental conditions and practical significance of QQ-bead in practical application, more detailed aeration intensity settings and more comprehensive investigations including biofouling control and sludge characteristics variations were essential. Meanwhile, aeration energy consumption accounts for the large majority of total energy requirements in an MBR [22]. The investigation focused on aeration intensity in QQ-MBR may provide a new view to decrease MBR energy demands.

In this study, three different levels of aeration intensity were operated in reactors with vacant beads and with QQ-bead. The MBR performance, sludge characteristics, and membrane biofouling control were investigated. At the same time, the energy consumption and the degree of membrane biofouling of the two reactors at different aeration intensities were compared and analyzed. The aim of this study was to find the optimal aeration intensity to maximize the QQ efficiency in biofouling control and achieve the goal of reducing energy consumption in MBRs as much as possible. The investigation which focused on aeration intensity in QQ-MBR may provide a new view to decrease MBR energy demands and also make a prospective study for the application of QQ strategy in the real sewage treatment system.

2. Materials and methods

2.1. Bacteria immobilization procedure

Rhodococcus sp. BH4 was used as QQ bacteria in this study and was immobilized in sodium alginate beads, a nontoxic substance to bacteria, according to Kim et al. [23], with a minor modification. The purified BH4 was cultured in Luria-Bertani (LB) medium at 30 ℃ for 24 h. Then, the bacterial suspension was centrifuged at 8000 rpm for 10 min. After repeating the procedure three times, it was resuspended in 10 mL of water and the final bacterial concentration was 250 mg BH4/mL of water. The bacteria suspension was uniformly mixed with 90 mL of the sodium alginate (3 g) suspension to make a BH4-sodium alginate suspension. The mixed suspension was dripped into 600 mL of 5 % (w/v) $CaCl_2$ solution through a syringe to shape a cell bead. The beads were formed and left in $CaCl_2$ solution for three h before being washed with plenty of deionized water, air-dried and stored at four ℃ for the subsequent application. The vacant beads were made by the same methods with an equivalent volume of deionized water replacing the bacteria suspension.

2.2. The MBR systems

Two 4.5 L MBRs with the party all operation were used for wastewater treatment (pH=7.0–7.5). The hollow fiber membrane was used in MBR. Each MBR was designed with a PVDF hollow (PVDF, KOCH, USA) fiber membrane module bearing the total filtration area of 0.02 m^2 and the pore size of 0.3 μm with the diameter of the membrane wire being 1.2 mm / 2.6 mm (inner diameter/outer diameter). Continuous filtration was driven by a peristaltic pump for constant filtration with a permeation flux of 18 L/ m^2/h. Air was supplied continuously through an air diffuser under the membrane module. According to the velocity gradient conversion in a previous study (et al., 2014). Three levels of operating schemes (ranging from 0.8 to 2.4 L/min, corresponding with 45 s^{-1} to 99.4 s^{-1}) were designed for two MBR. The setting covered the lowest to the highest range of shear regimes in applicable for the MBR, which was 0.8 L air/min, 1.6 mL air/min and 2.4 L air/min in control and QQ reactors. Mueller et al., ($year$) [24]. Before each operation, the whole sludge in two MBRs was collected, and the two parts were equally. Pressure gauges were used to monitor the TMP, and the logger and computer were capable of collecting and automatically recording the data. The number of vacant beads or QQ-beads inserted into experimental QQ-MBR in each stage was 80. When the TMP of the reactor reached 50 kPa, the data recording was stopped.

The MBR process company (Hunan Guozhen; Changsha, China) provided activated sludge, which was acclimated for 30 d with synthetic wastewater before experiments. The components of each 50 L synthetic wastewater (about 500 mg/L COD concentration) are as below: 25 g glucose, 1.25 g yeast extract, 1.25 g peptone, 12.5 g $(NH_4)_2SO_4$, 7.5 g K_2HPO_4, 7.5 g KH_2PO_4, 0.225 g $MgSO_4$, 25 g $NaHCO_3$, 0.099 g $CaCl_2$, 1.75 g NaCl, 0.06 g $CoCl_2$ and 0.005 g $FeCl_3$. There was no discharged sludge during this experiment and the HRT and the HRT and SRT were set to 12.5 h and 100d.

2.3. Extraction and determination of EPS

When the TMP of control MBR reached 50 kPa, SMP and EPS were extracted and measured. SMP in the mixed liquor of MBR was extracted and determined with the following program according to the previous study {[25] #40}: 35 mL of mixed liquor was centrifuged for 15 min under 8000 rpm, and then filtered the supernatant using a 0.45 μm Millipore filter. The filtrate can be used for determining SMP directly. Extracellular polymeric substances (EPS) were classified into loosely bound EPS and tightly bound EPS Called LB-EPS and TB-EPS. A modified thermal extraction method [26] was applied for extracting SMP, LB-EPS and TB-EPS in the mixed liquor. Biofilm on the membrane surface was removed by physical cleaning combined with 10 min of subsequent ultrasonic cleaning. The total EPS in the solution was then directly extracted according to the extraction method of TB-EPS. The extraction of SMP in the effluent was also the same as SMP in the mixed liquor. After extraction, the concentrations of proteins and polysaccharides in the SMP and EPS were measured by the modified Lowry method [27] and the phenol–sulfuric acid method, respectively. The EPS concentration was calculated according to the absorbance in the EPS standard curve and MLVSS ([28]).

2.4. Biofilm formation assay of activated sludge

The biofilm formation capacity of activated sludge at different aeration intensities was determined using 96-well flat flat-bottom styrene microtiter plates [29]. The sludge in two MBRs were gathered respectively, then adjusted their optical density (OD600) to 1.8. The microplate wells were inoculated using the mixed medium of diluted activated sludge (15 μL) and LB broth (5 μL). The culture dishes were incubated in the seal of 30 ℃ for 24 h. The biofilm formation capacity

Table 1
Comparison of COD removal at different aeration intensities.

	At LA intensity		At MA intensity		At HA intensity	
	Control MBR	QQ MBR	Control MBR	QQ MBR	Control MBR	QQ MBR
Efficiency (%)	92.4 ± 3.31	92.1 ± 4.10	89.6 ± 1.64	91.6 ± 4.36	91.9 ± 4.48	89.8 ± 1.65

was determined by crystal violet staining as follows: the wells were rinsed with PBS to remove the supernatant of the stock solution firstly. After the plates were dried completely, the wells were stained with 0.1 % (w/v) crystalline violet solution (200 μL) for 30 min, then washed with pure water. Then 200 μL of 95 % ethanol was used to extract the crystalline violet adsorbed on the biofilm surface of the wells. Finally, the absorbance (OD580) of crystal violet was measured by an ELIASA (M1000, TECAN), indicating its ability to sludge biofilm formation.

2.5. Analysis of energy consumption

The energy consumption of submerged MBR in this study was primarily divided into two parts: filtration energy and aeration energy. They were calculated according to Weerasekara et al. [17] and Lee et al. [30] as follows:

$$\text{Specific filtration energy}(\text{Wh}\Big/m^3) = \frac{1}{\eta_1 t_1}\int_0^{t_1} TMPdt \quad (1)$$

$$\text{Specific aeration energy}(\text{Wh}\Big/m^3) = \frac{P_w(kW) \times t_2}{\eta_2 \times Volume \quad of \quad permeate(m^3)} \quad (2)$$

Where η_1 and η_2 are the suction pump efficiency and the air compressor efficiency, which are assumed as 0.6 and 0.4, respectively. P_w is the power of the air compressor. The filtration time (t_1) was the same as the MBR operating time (t_2) because of the continuous operation.

2.6. Other item analysis

The COD, MLSS, MLVSS (mixed liquid volatile suspended solids) and sludge volume index (SVI) in influent and permeate were measured according to standard methods [31]. The zeta potential of activated sludge was measured using a Zetasizer Nano ZS instrument (Malvern, UK). The determination of relative hydrophobicity (RH) was analyzed as follows: A volume of 50 mL of mixed liquor was taken from two reactors. Then, an equivalent volume of n-hexane was added and agitated uniformly in a separation funnel for 30 min on a shaker. After standing for 30 min, the two phases were separated and, the aqueous phase was withdrawn. The MLSS of the aqueous phase was determined before and after the extraction. The RH was calculated as follows:

$$\text{RH}(\%) = \frac{C_i - C_e}{C_i} \times 100\% \quad (3)$$

where C_i is the MLSS concentration before extraction, C_e is the MLSS concentration after extraction.

To visualize the biomass accumulated at the membrane surface of different operation periods, the fouled membrane segments collected from reactors were stained using a Live/Dead BacLight Viability Kit (Molecular Probes, Invitrogen) according to the standard method and observed using a confocal laser scanning microscope (CLSM, TI-E + A1 SI, Nikon). The green and red colors in the CLSM images indicated live and dead cells, respectively.

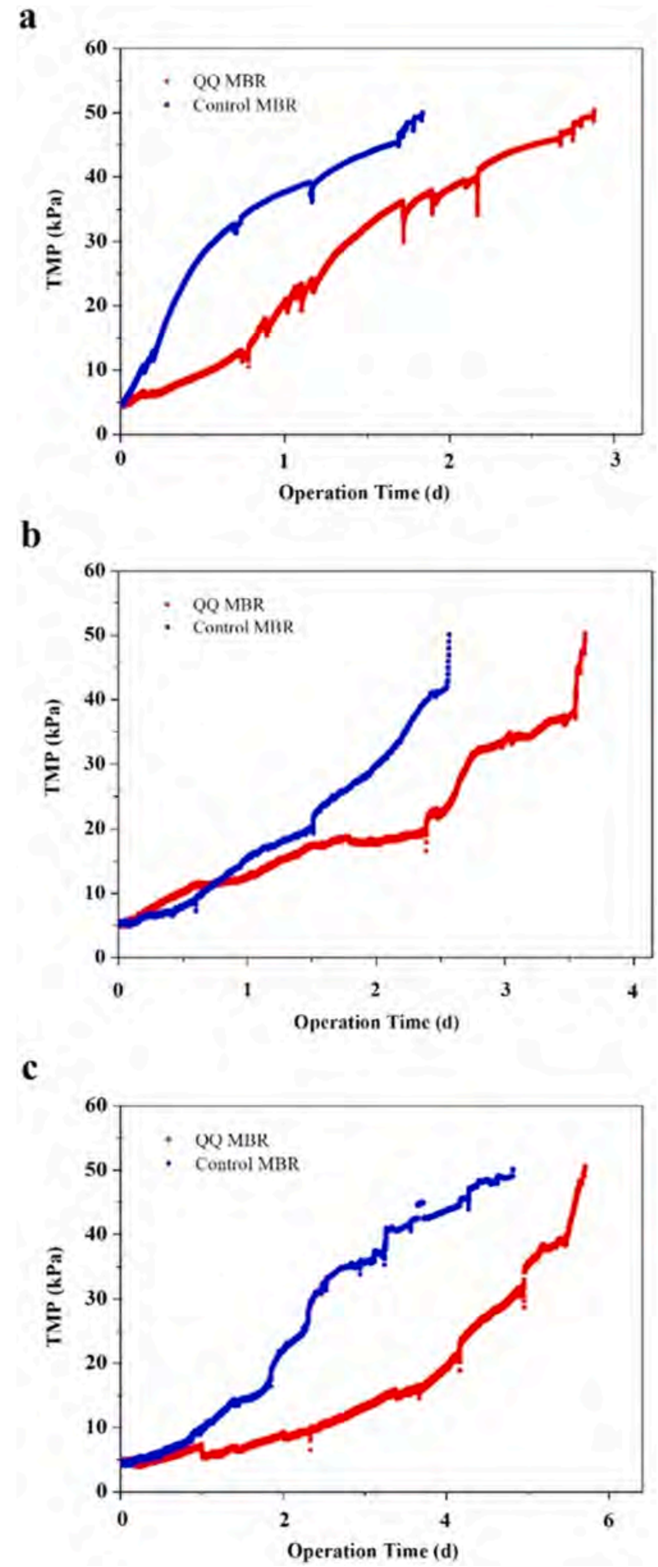

Fig. 1. TMP variations of two MBRs at different aeration intensities. (a) low aeration intensity; (b) middle aeration intensity; (c) high aeration intensity.

3. Results and discussion

3.1. Effects of aeration intensity on quorum quenching MBR performance

Considering that both aeration intensity and quorum quenching could impact microbial activity to some extent [16,21], the pollutant

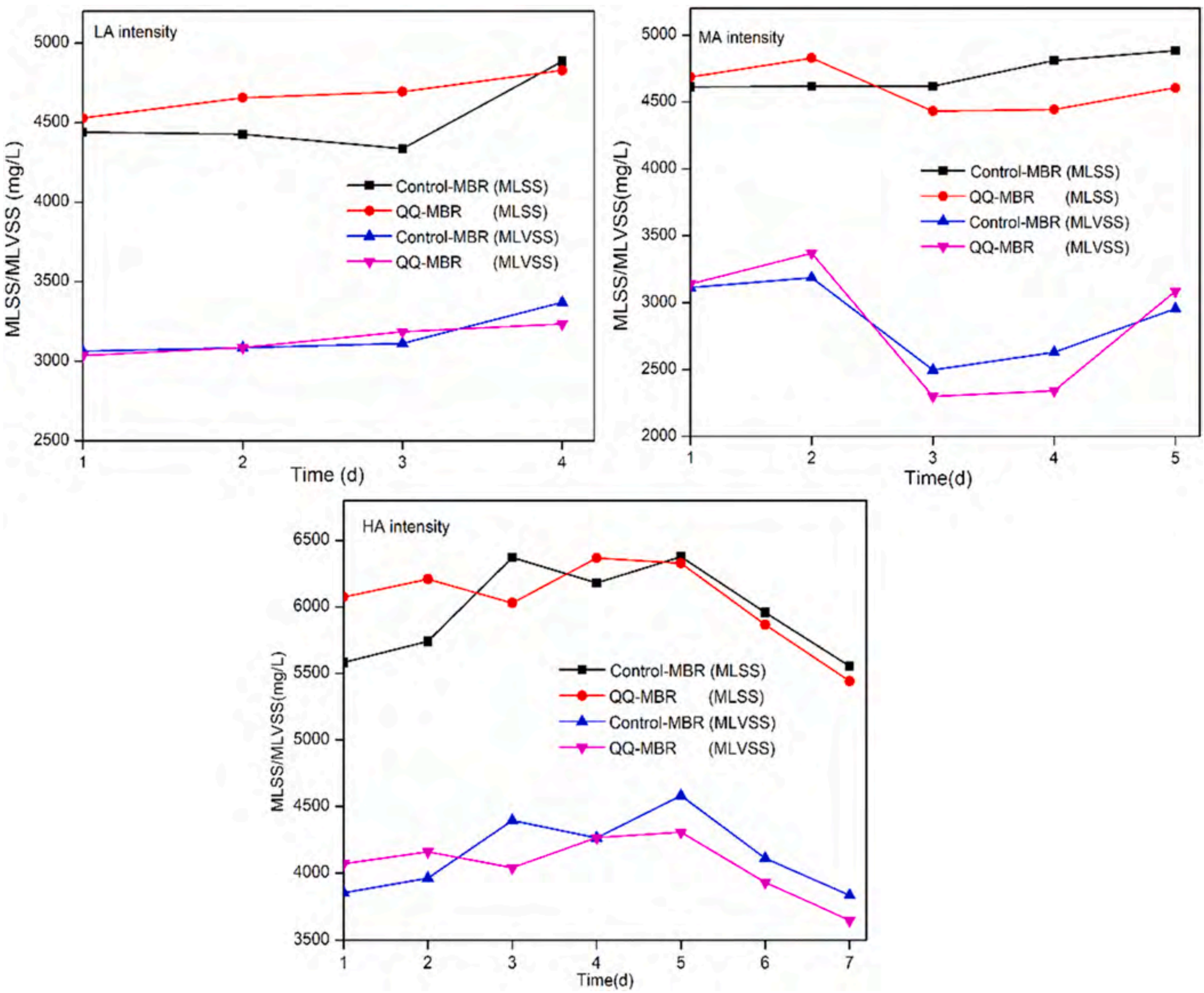

Fig. 2. The MLSS/MLVSS in control and QQ-MBR at three phases (LA, MA and HA).

removal efficiencies of two MBRs were routinely monitored in terms of COD concentrations in influent and permeated (Table 1). Both reactors exhibited a great performance, with outstanding COD removal efficiencies over 85 % at three aeration intensities. There was no significant difference in this index between the two MBRs throughout the entire experiment. Overall, both the changed aeration intensity and the addition of QQ had no negative effects on pollutant treatment performance in MBRs.

The profile for TMP buildup is an important indicator for assessing MBR membrane filtration performance because it can directly reflect the extent of membrane fouling [20]. The TMP results were replicated two times for each aeration intensity in MBRs. According to Fig. 1, the variations of TMP of two MBRs at different aeration intensities were displayed and replicated twice. A significant membrane fouling mitigation was observed in QQ -MBR at three aeration intensities compared with C-MBR, although mitigation efficiencies were diverse: low aeration (LA) intensity of approximately 37.9 %; middle aeration (MA) intensity of approximately 30.6 %; high aeration (HA) intensity approximately 17.9 %. Besides, the operation time (TMP reached 50 kPa) of two MBRs at high aeration intensity both exceeded 4 days, especially in QQ-MBR (about 6 days), which showed a better improvement in membrane fouling mitigation compared with other aeration intensities. This may result from the combination of coarse bubble scouring and QQ beads (QQ/physical washing) [23]. However, the lowest mitigation efficiency was observed at high aeration intensity with only 17.9 %. This is probably because the fouling layers on the membrane surface can be removed effectively by high-intensity air scouring, and it nullified most of the contribution of QQ activities to biofouling control [17].

Table 2
Comparison of sludge characteristics at different aeration intensities.

	LA intensity		MA intensity		HA intensity	
	C-MBR	QQ MBR	C-MBR	QQ MBR	C-MBR	QQ MBR
SVI (mL/g)	183.03 ± 3.86	177.77 ± 4.75	125.73 ± 4.41	119.91 ± 5.16	96.65 ± 8.57	70.72 ± 1.97
Zeta potential (mV)	-14.23 ± 0.77	-8.68 ± 0.57	-13.03 ± 0.50	-7.61 ± 0.90	-12.13 ± 0.13	-5.44 ± 1.08

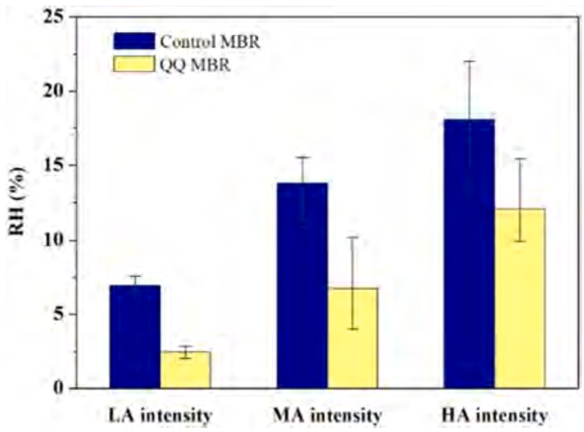

Fig. 3. Comparison of sludge relative hydrophobicity (RH) at different aeration intensities.

3.2. Sludge characteristics under different aeration intensity

Sludge properties are considered an important part of the evaluation of the MBR system, which were closely related to MBR filterability and the removal of pollutants [16,30]. Since QS can regulate bacterial gene expression and physiological behavior, which may affect the characteristics of sludge [32-34]. Aeration intensity, which is considered a vital factor for microbial activity, may also affect the characteristics of the sludge. Therefore, we determined the MLSS, MLVSS, sludge volume index (SVI), zeta potential, and relative hydrophobicity (RH) to investigate the effects of aeration intensity and quorum quenching on sludge characteristics. The MLSS and MLVSS in control MBR and QQ-MBR grew gradually and then leveled off (around 5000 mg/L) at three intensities throughout the experiment, that demonstrated QQ and intensities had no significant effects on MLSS/MLVSS (Fig. 2). It was shown in Table 2 that the SVI in QQ-MBR was slightly lower than in control-MBR in LA intensity (177.77 $\pm$ 4.75 compared with 183.03 $\pm$ 3.86) and in MA intensity (119.91 $\pm$ 5.16 compared with 125.73 $\pm$ 4.41), but at HA intensity, the SVI in QQ-MBR decreased 26.83 % compared with it in control-MBRs. Moreover, higher zeta potentials in QQ-MBR at three aeration intensities were observed compared with control-MBRs, especially up to $-$ 5.44 $\pm$ 1.08 in QQ-MBR at high aeration, which demonstrated that the sludge settleability and stability could be further enhanced with the elevating aeration intensity under QQ condition [35]. It was reported that the flocculation ability of sludge flocs is affected by its surface charge and settleability, and biofouling was reduced as bioflocculation improved. ([26,36] ; [37]). Although the sludge swelled slightly at low aeration intensity, there was no significant change in pollutant treatment and function of sludge. Besides, it was found that the effect of QQ enhancing the sludge settleability and stability was relatively significant at high aeration intensity.

Relative hydrophobicity (RH) was reported to impact bacterial adhesion and membrane fouling [16], which was also one of the important characteristics of the sludge. The measurement of sludge RH in two MBRs was shown in Fig. 3. At three aeration intensities, the RH of sludge in each reactor was all at a lower level (no more than 20 %) compared with other studies [16], and decreasing aeration intensity also led to the reduction of RH in control-MBR. The RH was reduced by 23.77 % (MA intensity) and 61.58 % (LA intensity) respectively compared to the RH at high aeration concentration. Meanwhile, we found that the RH of sludge in QQ-MBR was much lower than in C-MBR at three aeration intensities. This result indicated that quorum quenching could reduce the hydrophobicity of sludge flocs and then decrease the membrane fouling rate [38]. This may result from the positive correlation between sludge hydrophobicity and EPS [39].

3.3. Effects of aeration intensity and quorum quenching on biofouling control

3.3.1. SMP and EPS concentrations in mixed liquor and on the membrane surface

The concentrations of SMP and EPS (LB-EPS/TB-EPS) in mixed liquor and on membrane surfaces were measured in terms of polysaccharides and proteins (Fig. 4). It was showed in Fig. 4a-d that the addition of QQ significantly reduced the concentrations of SMP and EPS in mixed liquor, and the decrease of total SMP and EPS were all more than 20 % at three aeration intensities. However, QQ exhibited a better reduction effect for these three compounds at middle aeration intensity, especially for LB-EPS (From 81.035 mg/L to 28.258 mg/L). A similar result was also observed in Fig. 4d. Previous studies suggested that aeration intensity directly affected DO concentration and microbial activity in the reactor [21]. The concentration of SMP in QQ-MBR reduced by 44.71 % compared with control-MBR at MA intensity; otherwise, the reduction was 43.93 % at LA intensity and 28.72 % at HA intensity. Thus, these findings revealed that low aeration intensity (low DO) or high aeration intensity (high physical washing) might somewhat decrease QQ performance. Meanwhile, it was we found a relatively low level of total SMP and EPS in mixed liquor when the aeration intensity was increasing. The concentration of polysaccharides in control-MBR reduced by 39.97 % compared with QQ-MBR at HA intensity (Fig. 4d). The EPS content in the biofilm attached to the membrane surface was displayed in Fig. 4e, which also reflects the extent of membrane fouling indirectly. The number of EPS present in the biofilm of QQ-MBR was smaller than it of control MBR at three aeration intensities. QS was reported to promote biofilm formation by regulating EPS production [40,41]. Thus, the addition of QQ in the MBR could reduce the production of EPS effectively, and thereby control biofouling (biofilm formation). Similar to the result reflected by TMP buildup profiles, the overall level of EPS on membrane surface in two reactors was relatively small at high intensity aeration, probably because of the high-intensity physical washing and QQ effect. Yet, the EPS reduction efficiency between QQ-MBR and control MBR was the lowest at high intensity aeration.

SMP may enter membrane pores during filtration and partly attach in the pores owing to their jell-like properties [42,43], and they play a vital role in the formation of initial biofilm and the inside pores fouling [44]. The SMP concentration in effluent was measured at different aeration intensities to verify the influences of aeration intensity and QQ on inside pores fouling (Fig. 4f). Similar results as above indicated that SMP (polysaccharides and proteins) content in effluent was all reduced by QQ at three aeration intensities; however, there were relatively small SMP level and optimal SMP reduction efficiency in effluent at middle aeration intensity.

3.3.2. Biofilm formation capacity of activated sludge

To further verify the effectiveness of aeration intensity and QQ on biofouling control, and then explore the mitigation mechanism of membrane biofilm, biofilm formation assays were conducted from two reactors when the TMP of C-MBR reached 50 kPa [20]. The absorbance of crystal violet indicated biofilm formation capacity of activated sludge. Fig. 5 presented the biofilm formation capacity during three aeration rates, which suggested that the biofilm formation ability of sludge was decreased by the addition of QQ at three aeration rates, but this phenomenon was more significant at middle aeration intensity with the reduction as high as 39.84 % (i.e. a better QQ performance). Furthermore, the capacity of biofilm formation in both of MBRs was at a lower level (OD600 was 1.48 in C-MBR and 1.218 in QQ-MBR) at high aeration intensity, while combined with a high-intensity physical washing, which made the two reactors run normally for a long time (TMP buildup profiles).

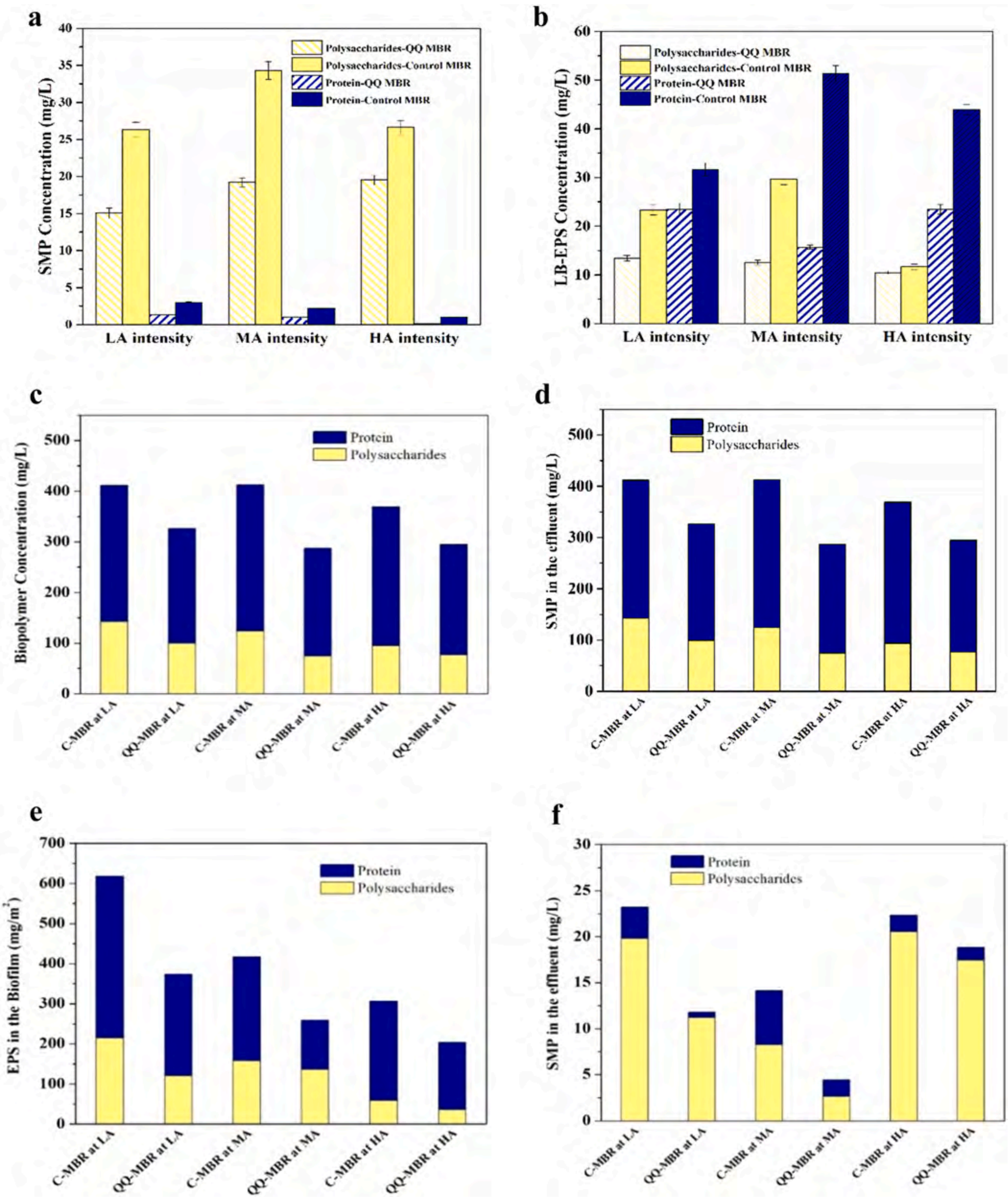

Fig. 4. SMP and EPS contents in two MBRs at different aeration intensities. (a)-(d) SMP, LB-EPS, TB-EPS and biopolymer (SMP+EPS) in the mixed liquor. (e) EPS presented in the biofilm attached to the membrane surface. (f) SMP in the effluent.

3.4. Effects of aeration intensity and quorum quenching on energy consumption

As one of the major factors that limit the widespread use of MBRs, the problem of energy consumption has always been a research hotspot in both academic and industrial fields [30]. To investigate the effects of aeration intensity in QQ-MBR and C-MBR on energy consumption, the total energy consumption of two reactors was divided into membrane filtration and aeration energies, and was compared at different aeration intensities (Fig. 6). At low, middle, and high aeration intensities, the

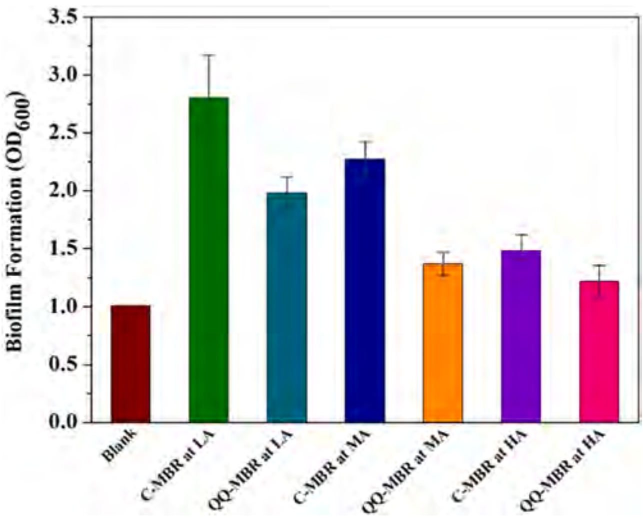

Fig. 5. Biofilm formation assay using activated sludge collected at different aeration intensities.

specific filtration energies of control MBR and QQ-MBR were 55.3 vs 46.7 Wh/m^3, 33.5 vs 34.0 Wh/m^3, and 45.2 vs 28.1 Wh/m^3, respectively (Fig. 6a). The results indicated that the specific energy consumptions for membrane filtration were relatively small, and QQ reduced the specific filtration energy, especially at high aeration intensity. This is because the time of QQ-MBR operating at lower TMP was longer at high aeration intensity. Meanwhile, at low, middle, and high aeration intensities, the specific aeration energies of the two reactors were 2.2 kWh/m^3, 4.4 kWh/m^3, and 6.7 kWh/m^3, respectively. Based on Fig. 6b, we found that the energy demands for aeration accounted for the highest energy consumption in MBR operations [45], and the specific aeration energy was positively correlated with aeration intensity.

Although the running performance of reactors was better at high aeration intensity (see Fig. 1), they consumed the most energy at the same time. To analyze the effect of QQ on aeration intensity, and explore the potential of QQ optimizing the aeration intensity, membrane fouling degrees of control MBR at middle aeration intensity and QQ-MBR at low aeration intensity were compared (Fig. 7). Generally, TMP rises more rapidly when aeration intensity is lower. However, although the aeration intensity was lower in QQ-MBR, its time of operating normally was longer than the control-MBR of middle aeration intensity (Fig. 7a). Also, less biomass accumulated at the membrane surface was observed in QQ-MBR (Fig. 7b-c). Thus, it can be concluded that the control effect of QQ on membrane fouling at low aeration intensity was still better than the

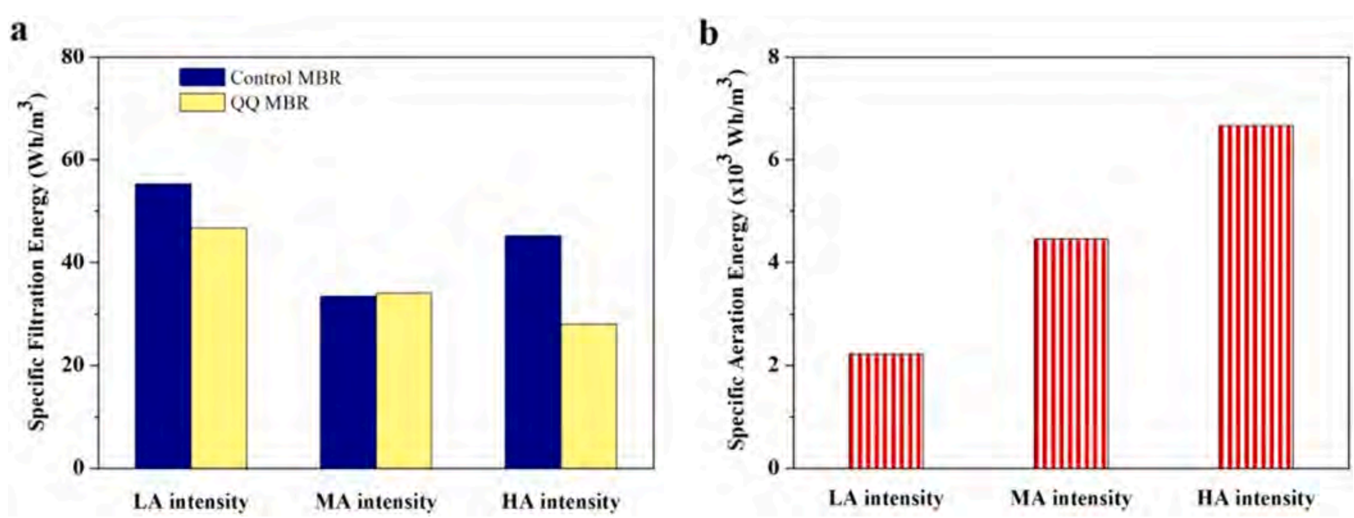

Fig. 6. Comparisons of specific energy consumption at different aeration intensities. (a) Membrane filtration energy; (b) Aeration energy.

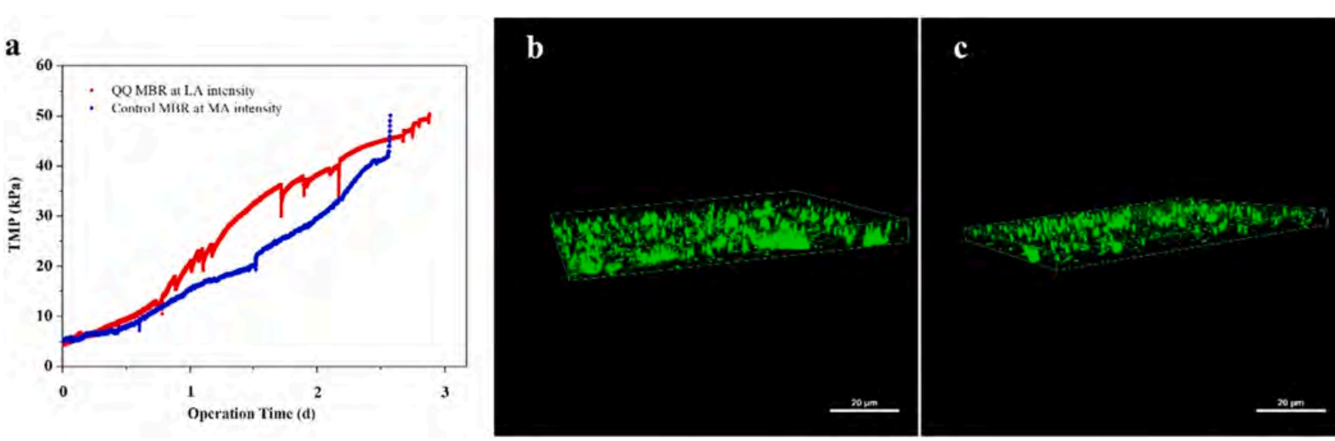

Fig. 7. Comparison of the membrane fouling degrees of control MBR at middle aeration intensity and QQ-MBR at low aeration intensity. (a) TMP variations of the two MBRs. (b)-(c) CLSM images of biomass accumulated at the membrane surface after 2.6 days of operation: (b) control MBR at middle aeration intensity; (c) QQ-MBR at low aeration intensity.

only physical washing at middle aeration intensity. Overall, high aeration intensity involved great energy consumption for sure and increased the operating costs of MBR. The addition of QQ could minimize the demanded aeration intensity without a significant effect on MBR operating normally, thereby decreasing the total energy consumption of MBR. It seemed that optimizing the air flow rate in QQ-MBR was significant, which can reduce membrane pollution and energy consumption on the premise of ensuring treatment efficiency.

4. Conclusions

The effects of aeration rate on QQ-MBR including the performance of activated sludge, membrane biofouling, and energy consumption analysis were investigated in this study. The MBR performance of QQ-MBR and Control-MBR was not significantly impacted at three levels of aeration intensities. Settleability and stability of activated sludge were improved to different extents at three aeration intensities with QQ capsules addition, which was significant relatively at HA. However, membrane biofouling control performance (biofilm formation and EPS variation) of QQ-MBR at MA showed an advantage, although the fouling time under HA was the highest due to its scouring action. In the analysis of energy consumption, the aeration energy consumption under the HA condition was obviously higher than that of the other two. As a result, MA was defined as the appropriate aeration intensity in the QQ-MBR for biofouling inhibition in this study. And the establishment of an aeration optimization model in QQ-MBR is worthy of further exploration.

CRediT authorship contribution statement

Kaixin Yi: Conceptualization, Methodology, Investigation, Visualization, Data curation, Writing – original draft. **Yichen Ouyang:** Investigation, Formal analysis, Writing – review & editing. **Jinhui Huang:** Conceptualization, Supervision, Project administration, Funding acquisition. **Haoliang Pang:** Conceptualization, Resources, Validation. **Chunhua Liu:** Project administration and Funding acquisition, Resources, Writing – review & editing. **Wenli Shu:** Visualization, Validation, Writing – review & editing. **Cong Ye:** Resources, Writing – review & editing. **Jinkun Guo:** 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.

Data Availability

Data will be made available on request.

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