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Effects of dissolved oxygen concentration on the performance of sponge membrane bioreactor treating hospital wastewater

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ABSTRACT

The performance of sponge membrane bioreactor (SMBR) is strongly dependent on operating conditions. Dissolved oxygen (DO) concentration is one of the key operating parameters in the SMBR process determining the mixing efficiency, floc generation, anoxic zone formation, and directly relating to pollutant removal efficiency and membrane behavior. This study aims to examine the effect of various DO concentrations on SMBR treating hospital wastewater. The objectives were to investigate the influence of three DO concentrations on (i) sludge characteristic, (ii) COD removal efficiency, (iii) nitrogen removal efficiency and (iv) membrane fouling in the lab scale SMBR. Consequently, the operation with DO_1 (7.15 ± 0.40 mg/L) achieved the highest MLSS concentration; however, it could consume excessive energy for aeration. The COD removal efficiencies were similar in three DO levels, ranging from 95% to 99%. The operation with DO_3 (1.58 ± 0.42 mg/L) resulted in the highest TN removal efficiency of 76% and TN denitrification percentage of 31%. Herein, sponges conditioned the denitrification process. The TN removal efficiency in SMBR was two times higher than the membrane bioreactor process. In addition, fouling was significantly improved at higher dissolved oxygen during operation period without any membrane cleaning.

Keywords: Sponge membrane bioreactor; Simultaneous nitrification denitrification; Membrane fouling; Dissolved oxygen; Hospital wastewater

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1. Introduction

Hospital wastewater (HWW) is known as a common source of pollutants, such as nutrients, pharmaceutical active compounds, radioactive elements and toxic chemicals [1]. Furthermore, these wastewaters also contain hazardous transmittance diseases including infected pathogens and viruses [2]. These compounds, which currently being discharged to the environment without any forms of treatment, certainly bring impacts not only for human health, but also for the ecosystem [3]. For example, the antibiotic resistance is an emerging problem due to the release of untreated wastewater [4]. The eutrophication that devastatingly damages the environment is also a well-known consequence. Therefore, ensuring HWW treated prior to discharging is an important step in the chain of environmental protection. In Vietnam, the implementation of Project 2038 - the master plan of waste treatment from 2011 to 2015 - and orientations toward 2020 established only 60% of the hospital wastewater treatment facilities.

There are plentiful researches considering HWW removal by several approaches, encompassing adsorption [5], constructed wetlands [6], advanced oxidation processes (AOPs) [7], membrane process [8] and hybrid system of biological and membrane process, namely membrane bioreactor (MBR) [9].

Recently, MBR technology is evident as a foremost wastewater treatment system, thanks to recent technical innovations (e.g., satisfied effluent quality, competitive footprint, less sludge production). The cost of employed membranes has decreased gradually [9]. However, membrane fouling is an inevitable problem associating during the operation process; one augments the hydraulic resistance to fluid flow, lessens the pollutant removal performance [10]. On the other hand, there is a considerable limit in nitrogen removal efficiency in aerobic MBR system [11]. Tackling the issues, several studies have been developed focusing on the mechanisms of pollutant removal process and reasons of membrane fouling. One of the options is to integrate MBR with sponge media called sponge MBR (SMBR). SMBR technology has been demonstrating its efficiency in pollutants removal and alleviating membrane fouling problem [12]. In this regard, Nguyen et al. [13] confirmed SMBR enhanced the nitrogen removal rate up to 0.011–0.020 mg total nitrogen (TN)/ mgVSS.d. Nevertheless, its performance is strongly dependent on such operating parameters (e.g., hydraulic retention time (HRT), sludge retention time (SRT), mixing intensity and dissolved oxygen concentration).

The dissolved oxygen (DO) concentration is a key operation parameter in SMBR technology. It determines the efficiency of the flocculation process itself, while it further contributes in the formation of membrane fouling and energy consumption [14]. Regarding nitrogen elimination, the simultaneous nitrification and denitrification (SND) happen inside the microbial flocs conditioning by DO concentration gradients and diffusional limitations [15]. It generates the anoxic microzones inner the sludge flocs; subsequently, the heterotrophic denitrifiers develop immensely and produce nitrogen gas as its common way. Through the more floc formation and pollutant removal efficiency, the loading of membrane, therefore, is reduced and alleviating membrane fouling accordingly. Optimizing DO concentrations in SMBR is obviously important. However, the studies on the effect of DO levels in SMBR process are still limited. As such, Cao et al. [16] examined the influence of DO from 1.5 to 5.5 mg/L in SMBR; so that, this work assessed SMBR performance at the more extended DO concentrations.

To this end, this study aims to examine the effect of various DO concentrations on SMBR system treating HWW. In details, the objectives were to investigate the effect of DO concentrations on (i) sludge characteristic, (ii) chemical oxygen demand (COD) removal efficiency, (iii) nitrogen removal efficiency and (iv) membrane fouling in the lab scale SMBR. The optimized DO concentrations were evaluated and served for any practical applications and modifications.

2. Materials and methods

2.1. Hospital wastewater and seed sludge

The wastewater in equalization tank of a hospital wastewater treatment system was employed as influent in this study. The collected wastewater was stored in cold room (5°C) prior use to reduce the biodegradation. Wastewater was maintained in the feed tank with the volume of daily use only. The constituent of this HWW is illustrated in Table 1. The additional sodium bicarbonate was applied to adjust pH in the MBR system from 6.5 to 7.

The seed activated sludge was collected from a full scale MBR in Sai Gon Tower (Ho Chi Minh city, Vietnam). The initial mixed liquor suspended solids (MLSS) concentration of seed sludge was approximately 4,400 mg/L. This sludge was cultured in Trung Vuong hospital's wastewater system in one week prior using for designed experiments.

2.2. Experimental setup

2.2.1. System setup

The research was conducted in a lab scale submerged SMBR with the dimensions of 28 × 8 × 60 cm corresponding to L × W × H (Fig. 1). The working volume of SMBR was 8 L. The influent wastewater was contained in a 100 L storage tank, being fed continuously into the reactor by a peristaltic pump (Cole Parmer, USA). The permeate after membrane process was collected in a 50 L tank. This system was controlled automatically by a timer, solenoid valves and digital pressure gauge. Air diffusers were established at the bottom

Table 1
Characteristic of employed HWW

Parameter	Value ± SD (n = 3)
pH	7.00 ± 0.15
COD, mg/L	400 ± 43
TSS, mg/L	320 ± 38
NH_4^+ - N, mg/L	6.6 ± 0.9
TKN, mg/L	32.3 ± 5.5
PO_4^{3-}-P, mg/L	1.2 ± 0.3
Alkalinity, mg/L	35 ± 4
Total coliform, MPN/100 mL	$2 \times 10^8 \pm 5 \times 10^3$

of the reactor near the rear end of the membrane module aiming at aeration and air scouring. The sensor was also installed in the reactor to control water level. The bioreactor was continuously aerated to maintain the different dissolved oxygen concentrations by the air blower.

2.2.2. Membrane module and sponge carrier

A submerged hollow fiber polyvinyldene fluoride microfiltration membrane module (Japan) was installed inside the reactor. The respective pore size and the surface area of membrane were 0.4 µm and 0.05 m^2. The digital pressure gauge (Omega, Australia) was used to record the trans-membrane pressure (TMP). Besides membrane unit, the aqua-porous gel (CC-10B) sponges (Nisshinbo, Japan) were added in the reactor. These sponges were made of polyester urethane with a porosity of 98% and the dimensions of each sponge were 0.8 × 0.8 × 0.8 cm (L × W × H). The sponges moving dominated 20% (v/v) working volume of the reactor.

2.3. Experimental design and operating conditions

Regarding operating conditions, HRT was fixed at 8 h to receive the desired organic loading rate (OLR). Furthermore, the SRT was designed at 20 d. The excess sludge was withdrawn with volume 0.4 L/d in the reactor to maintain the proper MLSS concentration of 1,350 mg/L. The sponges were kept suspending in the reactor to manage attached biomass inside sponges' pore. Regarding the membrane modules, the permeate pumps (Aquatec, USA) were operated in an intermittent mode (8 min on/2 min off) to maintain the membrane flux of 20 L/m^2.min. This system was scheduled in 180 d in continuous mode serving for this study.

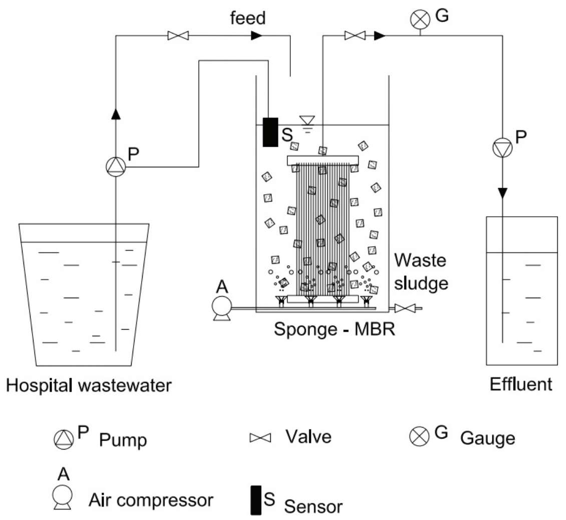

Fig. 1. Diagram of SMBR system.

Referring to experimental design, the performance of lab scale SMBR treating HWW was studied at different dissolved oxygen concentrations. In detail, the SMBR was operated at three DO levels of 7.15 ± 0.40 mg/L (DO_1); 5.33 ± 0.32 mg/L (DO_2); 1.58 ± 0.42 mg/L (DO_3). These DO concentrations were applied consecutively from DO_1, DO_2 to DO_3 during 180 d of reactor operation. The values of operation periods, HRT, SRT and OLR corresponding to DO concentrations are given in Table 2.

The sludge characteristics, encompassing MLSS and settling behavior, were examined. Furthermore, the influence of DO concentrations on COD and N removal efficiency was investigated. Besides, the membrane fouling identity was also recorded.

2.4. Sampling and analytical methods

The samples of NO_3^--N, NO_2^--N, NH_4^+-N, TKN, COD, PO_4^{3-}-P, MLSS were analyzed following Standard Methods [17] with the frequency of 3 times per week. The MLSS in sponges was examined which adapting from the procedure of Escolà Casas et al. [18]. In this regard, ten sponges were collected randomly and placed on a ceramic dish. These sponges were dried in 24 h at 105°C and weighed. Afterward, the media was rinsed in NaOH (2 M) to detach the biomass, and then cleaned with distilled water. These sponges were re-dried at 105°C in 24 h and weighed again. The amount of biomass attached in the sponges was calculated through the weight difference before and after cleaning.

The DO and pH in the reactor were measured by a DO meter (HI 9146, Hanna Instruments, Canada) and pH meter (IP 65, Milwaukee Instruments, USA) with the frequency of 3 times per week. Regarding TMP, it was measured online in the reactor with the frequency of 5 d/wk. It was recorded at 4 min counting from the beginning of operation cycle (total 8 min). The influent samples were taken in the storage tank, whereas the effluent samples were collected in the valve after permeate pump. The sludge samples were taken via the bottom valve of the reactor.

Nitrogen balance was calculated according to Eq. (1). Nitrogen assimilated in biomass was estimated based on that nitrogen accounting of 12% VSS [19].

$$TN_{in} = TN_{out} + TN_{assimilated} + TN_{denitrification} \quad (1)$$

Regarding membrane resistance, it can be calculated through the Darcy equation as follows:

$$J = \Delta P_{\mu} \times R_t \quad (2)$$

Table 2
Operating conditions of SMBRs

Component	DO (mg/L)	Period	HRT (h)	SRT (d)	OLR (kg COD/m^3.d)	F/M (kg COD/kg MLSS.d)
DO_1	7.55 ± 0.40	Day 1st to 72nd	8	20	1.19 ± 0.22	0.16
DO_2	5.33 ± 0.32	Day 73rd to 144th	8	20	1.33 ± 0.24	0.19
DO_3	1.58 ± 0.42	Day 145th to 181st	8	20	1.23 ± 0.31	0.19

$$R_t = R_m + R_c + R_f \quad (3)$$

where J is the permeate flux, ΔP is the TMP, M is the viscosity of permeate, R_t is the total resistance, R_m is the intrinsic membrane resistance, R_c is the cake resistance, R_f is the fouling resistance caused by the adsorption of soluble matters and pore blocking.

Flux (J) and TMP data were used to calculate the component resistances based on Eqs. (2) and (3). Total resistance (R_t) was calculated from the final flux and TMP upon the end of operation with pure water. The cake resistance (R_c) associating to attachment of the cake layer on membrane surface could be cleaned manually by tap water. Thus, the total of R_f and R_m could be received by the filtration of pure water after removing the cake layer. Subsequently, R_c could be achieved by the subtraction of R_t and sum of R_f and R_m. Afterward, the membrane was chemically cleaned by soaking in 4 h with 0.5% NaOCl and NaOH 4% solutions to determine the R_m by the filtration of pure water. Finally, R_f was determined by subtracting R_m.

In this study, the representative samples at steady-state conditions were examined in triplicate to ensure the requirement of accuracy and repetition of the experiments.

3. Results and discussions

3.1. Effects of DO concentrations on sludge characteristics

3.1.1. MLSS concentration

Mixed liquor suspended solid is an important parameter to evaluate the microbial consortium's growth in the reactor. These microorganisms have a close link to DO concentration, which provides oxygen for their respiration, stimulates pollutants consumption and encourages reproduction. With reference to DO_1 concentration, the average MLSS concentration was 7,628 mg/L. During the first week, the suspended biomass decreased slightly from 7,660 to 6,891 mg/L. MLSS was observed increasing steadily to 8,000 mg/L. This can be explained by the adaptation of microorganism to the new cultured condition. Furthermore, the proper OLR in this stage (1.19 ± 0.22 kg COD/m^3.d) provided at its sufficient nutrients for microbes. The biomass in sponges tended to increase slightly because of the ongoing attached process of the sludge into the sponge, dominating 41% total MLSS. The details of MLSS in sponges, wastewater and their ratios are illustrated in Fig. 2.

Regarding DO_2 concentration, a difference in terms of MLSS compared with DO_1 was observed. Generally, it is likely the MLSS concentration in this stage is lower which being of 6,860 mg/L. However, the MLSS concentration fluctuated from 6,000 to 7,000 mg/L due to the variation of influent COD concentration. In the first week, the suspended MLSS reached a peak of 7,397 mg/L; subsequently, it was almost behind that level. Although, OLR in this stage (1.33 ± 0.24 kg COD/m^3.day) was higher than the previous stage (1.19 ± 0.22 kg COD/m^3.day), the MLSS concentration did not augment accordingly. The only possible reason was the reduction of employed DO (5.33 ± 0.32 mg/L) while the DO concentration of 7.15 ± 0.40 mg/L was previously applied. To reproduce new cells in aerobic process, the critical elements of C, N, P and O were necessary. Nevertheless, the shortage of O compounds in this stage resulted in the reduction of MLSS concentration. Regarding biomass concentration in sponges, it accounted for 45% of total MLSS which was slightly higher than DO_1 period. The lower DO concentration also reduced the hydraulic mixing from air blower. This turned into the less mobile performance of sponges in the reactor.

The operation with DO_3 achieved the lowest MLSS concentration of 6,562 mg/L. The biomass in the sponges was quite stable while MLSS in wastewater reduced significantly from 4,000 to 2,000 mg/L. The biomass in sponges dominated 53% of the total MLSS. This DO level (1.58 ± 0.42) was below 2 mg/L and this provided less sufficient oxygen requirement. Consequently, the suspended MLSS decreased noticeably. However, biomass in sponges was stable for some reasons.

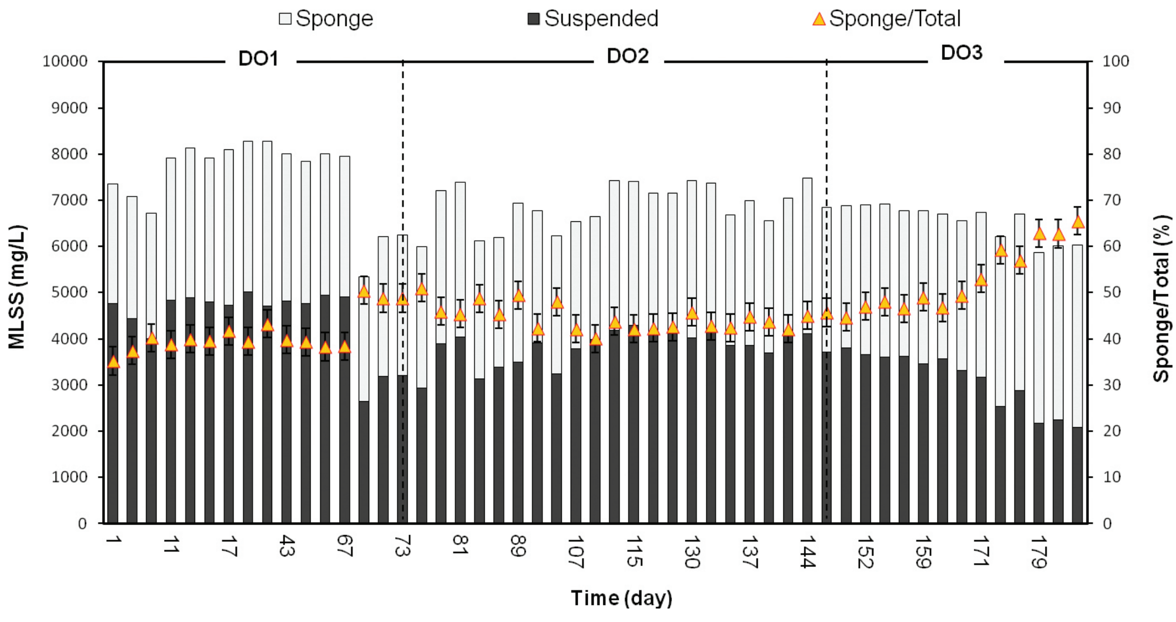

Fig. 2. Fluctuations in MLSS concentration and Sponge/total ratio during the treatability study.

These sponges could prevent the influence of fluid shearing and offer sheltered anchoring points via their porosity; therefore, biomass in sponges was maintained accordingly.

Overall, the operation with high DO level of 7.15 ± 0.40 mg/L achieved the highest MLSS results thanks to the adequate nutrients concentration and oxygen for microorganism reproduction. However, the viscosity of sludge augmented dependently with MLSS concentration [20,21]. Therefore, MLSS generated by DO_2 and DO_3 was more appropriate for SMBR operation. Congruently, Alsalhy et al. [22] found that SMBR perceived its promising efficiency at MLSS of 10 m/L, complying to DO concentration from 1 to 4 mg/L. During the three operation stages, the ratios of MLSS and MLVSS were consistent, illustrating the stable operation and sludge characteristic of the system (Table 3).

3.1.2. Settling characteristics

The settling characteristic of employed sludge was evaluated through the Sludge Volume Index (SVI). Regarding SVI results, their values decreased corresponding to the reduction of DO level; but they varied from 100 to 200 ml/g indicating a good settling characteristic. The SVI of DO_1, DO_2 and DO_3 were 184 ± 12, 124 ± 26 and 122 ± 18 mL/g, respectively. In DO_1 operation stage, the floc formation was difficult which was due to the high level DO and disturbed mixing condition. This hydraulic pattern lessened a chance to configure flocs. This sludge was more difficult to settle. However, the second and third stages with DO_2 and DO_3, respectively, with SVI around 120 mL/g occupied much easier settling characteristics. The gently mixing encouraged the generation of bigger floc size. Congruently, Nguyen et al. [23] figured out SVI in SMBR was less than 100 ml/g in DO from 3.0 to 3.2 mg/L, but significantly lower MLSS of 250–5,000 mg/L. The higher DO concentrations resulted in the higher SVI values accordingly.

Table 3
MLVSS/MLSS ratios and sponge biomass/total MLSS ratios in the three stages

	DO_1	DO_2	DO_3
MLVSS/MLSS	0.71 ± 0.01	0.70 ± 0.01	0.69 ± 0.01
Sponge biomass/ Total MLSS	0.41 ± 0.04	0.45 ± 0.03	0.53 ±0.07

3.2. Effects of DO concentrations on COD removal efficiency

Regarding COD removal, the significant treatment efficiencies were achieved in three DO levels, ranging from 95% to 99% (Fig. 3). The COD concentrations in the effluent were below 20 mg/L; sometimes were minimized under 5 mg/L.

According to literature, the DO level from 4 to 8 mg/L was favorable for pollutants removal [24] which agreed with this finding. Considering the aeration cost, the DO concentrations from 2 to 4 mg/L were recommended. The COD removal efficiency in the study of Meng et al. [24] was 93% and photosynthetic bacteria of *Rhodopseudomonas* was applied. However, this work employed mixotrophic bacteria consortium which may much more complicated. Therefore, the potential of treating higher-strength wastewater of this study is evident. Furthermore, Faust et al. [25] compared the two DO concentrations of 4 and 1 mg/L in MBR systems. The higher DO concentration resulted in a more significant bioflocculation and COD removal efficiency (92%) than the lower DO value (63%). The reason was the more generation of extracellular polymeric substances and sufficient distribution of multivalent cations, such as calcium, iron and aluminum, in higher

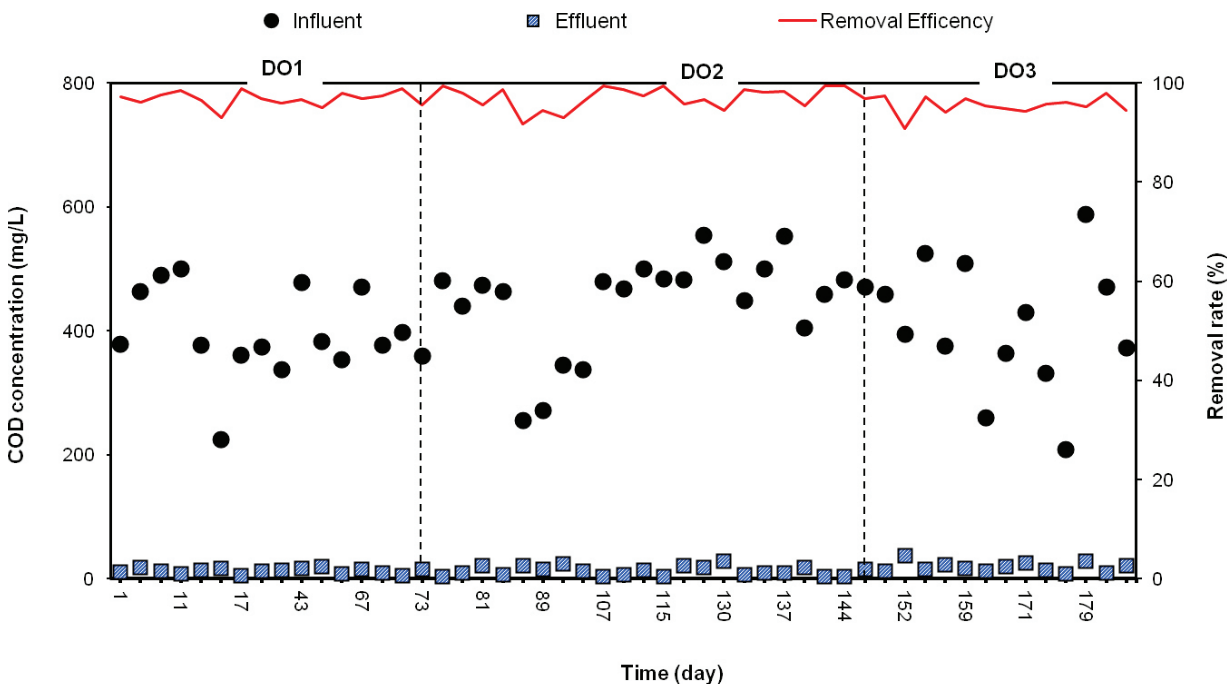

Fig. 3. COD removal efficiencies at different DO concentrations.

DO condition. The more extracellular polymeric substances were generated, the more COD was utilized as substrate [26]. The influent COD concentration was also similar to the range of this study, being from 300 to 500 mg/L. In another study, Gao et al. [27] found that microbial diversity in MBR system operating at DO of 2 and 4 mg/L was similar; but it became less while DO was 0.5 mg/L. This microbial community was a key success to remove COD in wastewater. In this regard, the COD removal efficiency in DO_3 (1.58 ± 0.42) was still efficient (95%) thanks to the growth of microbial community. Also, Cao et al. [16] agreed that DO concentration of 2.5 mg/L was optimal for COD removal (92.43%) applying in moving bed sequencing bioreactor. Thus, the DO_2 and DO_3 achieved a satisfying COD removal efficiency.

3.3. Effects of DO concentration on N removal

The concentrations of NH_4^+-N, NO_2^--N, NO_3^--N and TN were examined to assess the nitrogen removal performance under different DO conditions. With reference to NH_4^+-N, the removal efficiency in DO_1, DO_2 and DO_3 periods were 74%, 73% and 55%, respectively. Theoretically, 4.57 g oxygen is required to oxidize 1 g NH_4^+ to NO_3^- [19]. Nevertheless, the DO_3 concentration (1.58 ± 0.42 mg/L) was not equitable for a completed NH_4^+-N oxidation because the nitrification process in biofilm was limited, leading to a NH_4^+-N removal efficiency of only 55% (Table 4).

This result was congruent with the finding of Cao et al. [16] in the moving bed SBR. In details, the DO concentration of 5.5 mg/L enhanced the conversion of NH_4^+-N to NO_3^--N at its highest efficiency (97.89%); while it received only 42.04% with DO of 1.5 mg/L. According to the author, DO concentration of 2.5 mg/L achieved the highest N removal efficiency of 83.73%; whereas the increase of DO concentration decreased N treatment although it could augment the conversion of NH_4^+-N in some extent. For example, TN removal efficiency was 52.51% at DO of 5.5 mg/L. In this study, the N removal efficiency of 73% and 76% were possessed at DO_2 (5.33 ± 0.32 mg/L) and DO_3 (1.58 ± 0.42), respectively, which higher than Cao et al. [16], although the inlet nitrogen concentration was equivalent. The sponges herein played an important role in SND process. The formation of DO gradient inside the sponges encouraged SND process immensely by forming anoxic zones [22,28]. This anoxic environment in the sponges or in the inner parts of biofilms encouraged heterotrophic denitrifiers to produce nitrogen gas [29]. Furthermore, the anoxic zone inside the sponges conditioned the denitrification effectively [1]. The TN removal efficiencies of this study were also more competitive than Nguyen et al. [1] of which 25% to 52% at various membrane fluxes. The study employed DO concentration of beyond 4 mg/L and similar wastewater characteristic, receiving equivalent MLSS from 5,000 to 7,000 mg/L. We explained this difference via the consecutive adaptations of DO concentration, which stabilized both the nitrifying and denitrifying microbial consortium in the bulk liquid and sponges, respectively. This evidence was clarified through the unchanged MLSS and MLVSS/MLSS ratios in the whole experiments. Also, compared with the conventional MBR, this SMBR achieved two-fold higher N removal efficiency at the similar operating conditions [12].

Table 4
N removal efficiency at different DO concentrations

Parameter	Dissolved oxygen (mg/L)		
	DO_1	DO_2	DO_3
Influent NH_4^+-N, mg/L	7.45	3.59	1.04
Permeate NH_4^+-N, mg/L	1.68	0.77	0.43
Nitrification efficiency, %	77	73	55
Influent NO_3^--N, mg/L	0.35	0.46	0.24
Permeate NO_3^--N, mg/L	2.69	0.90	0.14
Influent TN, mg/L	22.83	19.76	16.98
Permeate TN, mg/L	7.06	5.26	4.01
Removal rate TN, %	68	73	76

Referring to SND performance, the highest percentage of TN denitrification was observed at DO_3 (31%) and it gradually reduced following the increase of DO level, such as DO_2 (23%) and DO_1 (19%) (Fig. 4).

The higher DO concentration offered more oxygen penetration through the flocs; so that the anoxic zone reduced accordingly. Hence, low DO concentration can bring benefit to the denitrification process, proliferating denitrifying bacteria [30]. The TN concentrations in the permeate decreased with lower DO concentrations, namely DO_1 (38%), DO_2 (25%) and DO_3 (21%), indicating that DO concentration was the most important factor in regulating SND process in the SMBR. Fan et al. [31] recommended the appropriate DO of 0.5 mg/L for an effective SND process. At this low DO level, nitrifying community possessed higher activity, improving oxygen mass transfer of gas and liquid phases, especially long term operation; although the adaptation in some first days was necessary [32,33]. Previously, some authors stated the low DO condition reduced the activity of ammonia-oxidizing bacteria and nitrite-oxidizing bacteria [34,35]. The removal efficiencies and TN concentrations in the permeate of this work were significant which complied to Vietnam National Technical Regulation on health care wastewater – QCVN 28:2010/BTNMT (10 mg NH_4^+-N/L and 30 mg NO_3^--N/L).

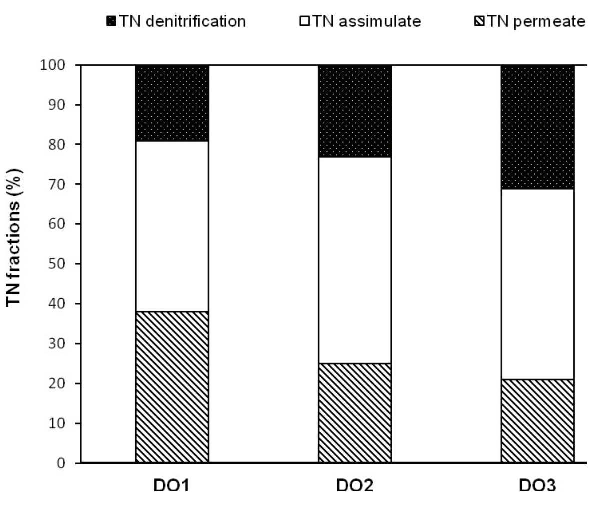

Fig. 4. TN fraction of the concentration difference between effluent and influent under different DO conditions.

3.4. Membrane fouling behavior

The variation of TMP in the SMBR was monitored at a constant flux of 20 L/m^2.h illustrated in Fig. 5. Regarding DO1, the increase in TMP was slower and stable until 67 d of operation without membrane cleaning. The operation of DO2 and DO3 were witnessed a rapid rise of TMP to 60 kPa in 40 and 30 d, respectively. On the other hand, the lower DO condition, such as DO3, decrease the collision of sponges and membrane fibers, leading to the more biofilm formation on membrane surface. Consequently, the membrane became fouling more frequently. In this regard, Cho and Fane [36] explained the extracellular polymeric substance (EPS) was the main reason causing membrane's pores blocking. A considerable amount of EPS was observed while the DO concentrations decreased from 4 to 1 mg/L [25]. For this reason, the local flux increased in open pores and exceeded the critical flux of the feed solution, subsequently, resulting in a rapid TMP rise. According to Nguyen et al. [1], the SMBR possessed 3.8 to 11 times fewer fouling rate compared with the conventional MBR. The involving of sponges/flocs in MBR system alleviated the influence of EPS and other disturbance, such as soluble microbial product (SMP) [14]. In previous study, the SMBR was functioned efficiently more than 92 d prior to reaching TMP of 20 kPa [37], coupling DO concentration from 0.4 to 3.4 mg/L. The MLSS concentration and membrane flux, however, was 4,400 mg/L and 10 L/m^2.h, respectively, which was two-fold less than this study.

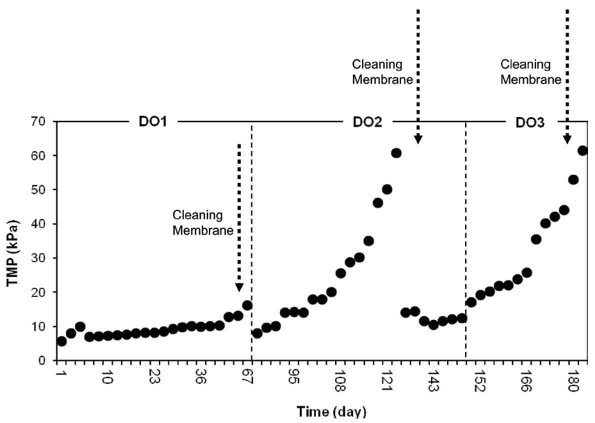

Fig. 5. TMP variation of SMBR system under different DO conditions.

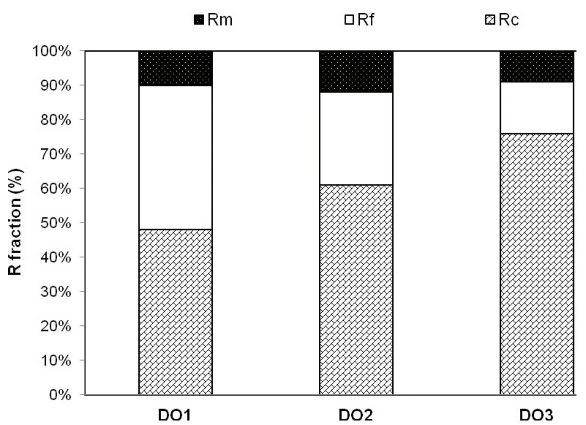

Fig. 6. Membrane resistances fraction.

Regarding the contribution of resistance fraction, the major resistance in the SMBR was from intrinsic membrane (R_m) [1,28]. However, our work found that the cake resistances (R_c) of the SMBR dominated 76%, 61% and 48% of the total resistances at the DO_3, DO_2 and DO_1, respectively (Fig. 6). The R_c values of these researches were only from 14%–18%. There were two reasons for this difference, encompassing applied sponge size and fluxes. The sponge size in this study was 0.8 × 0.8 × 0.8 cm, whereas Nguyen et al. [1] and Yang et al. [28] employed sponge size of 2 × 2 × 2 cm and 1 × 1 × 1 cm, respectively. The larger sponge size brought more collision with membrane fiber; therefore, the R_c diminished accordingly. These authors also operated SMBR with fluxes from 2 to 6 L/m^2.h which were three times less than this work. Hence, the chance of generating higher R_c in this study was obvious. Nevertheless, SMBR was reported to be more effective in managing cake layer resistance at its 86%–96% than the MBR system [22,28].

4. Practical applications and future perspective

The results of this study are potentially applicable in practice. First, the suitable DO concentration can be referred to manage the SMBR system. Although, DO_1 received highest MLSS; however, DO_2 and DO_3 were likely a proper choice thanks to the competitive COD and N removal efficiency. As mentioned beforehand, the DO_3 concentration offered co-benefit of indulging nitrifying and denitrifying bacteria and reducing electricity consumption, especially in long term operation and full-scale wastewater treatment system. The operation with different DO concentrations from high to low values likely resulted in more COD and N removal efficiency in hospital wastewater treatment. The recycling of grey wastewater in Vietnam has been considered with MBR process elsewhere [38]. The COD removal efficiency was 92% while its concentration in the permeate was approximately 28 mg/L. The application of SMBR can minimize COD in the permeate below 20 mg/L. Furthermore, the MBR system integrated into decentralized wastewater system in Vietnam, proposed by Sartor et al. [39], can be modified with SMBR. In industry sector, the textile wastewater treatment, employed MBR by Luong et al. [40], is also feasible with SMBR. Second, the control of membrane fouling can be applied from this study.

The comparison with other studies regarding pollutants removal efficiency and potential applications are illustrated in Table 5.

5. Conclusion

Overall, DO levels possessed the certain influences on SMBR operation, focusing on the sludge characteristics, COD and N removal efficiency and membrane fouling. In details, the following conclusions were drawn from the achieved results:

- The operation with DO level of 7.15 ± 0.40 mg/L achieved the highest MLSS concentration thanks to the sufficient nutrients concentration and oxygen for microorganism reproduction. However, it could consume excessive

Table 5
Comparison with other studies and practical applications

No.	Reactor types	DO concentration (mg/L)	Organic loading (kg/m^3.d)	HRT (h)	SRT (d)	COD influent (mg/L)	COD effluent (mg/L)	COD removal efficiency (%)	N influent (mg/L)	N effluent (mg/L)	N removal efficiency (%)	Fouling period (d)	Flux (L/m^2.h)	Applications	References
1	Sponge MBR	7.55 ± 0.40 (DO_1)	1.19 ± 0.22	8	20	400 ± 43	<25	97 ± 2	22.83	7.06	68	67	20	Hospital wastewater	This study
		5.33 ± 0.32 (DO_2)	1.33 ± 0.24	8	20		<25	97 ± 2	19.76	5.26	73	40			
		1.58 ± 0.42 (DO_3)	1.23 ± 0.31	8	20		<25	95 ± 2	16.98	4.01	76	30			
2	Sponge granular activated carbon MBR	1–4	–	4	25	700 –860		85	45.8 ± 2.3	0	100	21	63.8	Hospital wastewater	[22]
3	Moving bed MBR	1.5, 2.5, 3.5, 4.5 and 5.5	–	12	6	213–286	18.67–24	92.43	21.1–30.8	7.11–13.75	83.73	–	–	Synthetic wastewater	[16]
4	Sponge MBR	4	0.15 ± 0.04–0.39 ± 0.13	7.3–22	45	38–224	11–16	85 ± 10–89 ± 9	19.6–57.1	18.5 ± 7.0– 23.3 ± 5.0	25 ± 1– 52 ± 13	85	2– 6	Hospital wastewater	[1]
5	Sponge MBR	4	–	2–8	30	22–167	6.3	87–94	–	2.7	57–84	15–58	5–20	Aquaculture wastewater	[12]
6	Biofilm carriers membrane bioreactor	0.4– 3.4	–	10	10	467	24.5	94.2	40.4	–	37.3–51	92	10	Municipal wastewater	[37]
7	Biological-band and suspended-honey-comb carriers MBR	4	–	5–9	30	100–280	–	>90	25–46	–	50–70	60	20	Municipal wastewater	[41]
8	Sponge tray MBR	3.0–3.2	–	–	–	330–360	–	95	18–19	3–3.7	64.55–83.59	20	12	Synthetic wastewater	[23]

energy for aeration. Therefore, the SMBR employing DO_2 (5.33 ± 0.32 mg/L) and DO_3 (1.58 ± 0.42 mg/L) was more appropriate for energy saving.
- The COD removal efficiencies were similar in three DO levels, ranging from 95% to 99%. The COD concentrations in the permeate were below 20 mg/L.
- The operation with DO_3 resulted in the highest TN removal efficiency of 76%. Furthermore, the highest percentage of TN denitrification was observed at DO_3 (31%) and it gradually reduced following the increase of DO level, such as DO_2 (23%) and DO_1 (19%). Herein, sponges conditioned the denitrification process and the TN removal in SMBR was two times higher than that in the conventional MBR and it would depend on the maintained DO concentration in the bioreactor.
- In the lower DO condition, such as DO_3, the decrease of sponges' collision led to the more biofilm formation on membrane surface.

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