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Performance evaluation of a novel eductor-based MBR for the treatment of domestic wastewater

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ABSTRACT

The performance of a patented novel eductor-based MBR was studied in comparison with a conventional diffuser for the treatment of domestic wastewater. The eductor showed a high rate of oxygen transfer over the diffuser (K_La of 18.49 and 5.6/h, respectively, for the eductor and the diffuser in clean water). Higher recirculation rate through the eductor increased mixing inside the MBR tank and resulted insignificantly less membrane fouling compared to the diffuser (when the MBR was operated in continuous permeation mode; without any back-washing). The COD and ammonia removal efficiency of the MBR was also found to be higher with the eductor than the diffuser. The eductor was found to have great potential to be used as an aerator as well as a mixer if operated in a large scale of application in wastewater treatment by MBR.

Keywords: MBR; Aeration; Diffuser; Eductor

1. Introduction

MBR is a significantly important technology in the field of wastewater treatment. The uses of MBRs have been increased dramatically in the last few years to achieve an excellent quality of effluent to be reused or recycled [1]. MBR is a wastewater treatment process which combines biological treatment and physical separation by membrane filtration. It has the advantages of more constant permeate quality, independent control of solid and hydraulic retention times, operation at higher mixed liquor suspended solids (MLSS) concentration, etc. [1].

Inspite of having many advantages the MBR has a major drawback which is the membrane fouling. Up to 70% of the total energy demand for MBR systems is for fouling mitigation by air scouring which hinders the wider use of MBR [2]. Air scouring detaches particles from membrane surface into bulk solution and thereby leads to the prevention on the formation of cake layer [3]. So far, many studies have been conducted to optimize the aeration rate and aerator's position to mitigate membrane fouling [4]. Intermittent aeration has also been mentioned in the literature as the effective means of preventing fouling [5,6]. It is

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worth mentioning that the aeration protocols adopted in most of the studies were mainly with the different types of air pumps which bubbled the air in the MBR through different types of diffusers [7,8]. Although somewhat effective at reducing membrane fouling rates, known methods of fouling mitigation may not be optimum. For example, known methods of membrane fouling mitigation may not effectively promote back-transport at high rates enough for widespread applications of MBR processes and at high flux the aeration plays a less significant role in membrane fouling control [9,10].

In a different approach by Park et al., a Venturi nozzle was used to aerate the membrane-coupled high-performance compact reactor (MHCR), and was reported to have significant improvement in terms of membrane fouling control and organics removal [11].

In light of Park's study, we used a novel eductor [12] for the treatment of domestic wastewater in a MBR. This eductor also works with the Venturi principle but is unique in its kind that when the liquid is recirculated through the eductor, it not only draws the air from the atmosphere but also drags the surrounding liquid inside it, resulting in the formation of a huge jet mixture of liquid and air. The fact that the overall mixing (influent, biomass, and the air) in the reactor and the shearing forces of both the liquid and the air along the membrane surface are the major factors contributing towards the overall performance of the MBR [13] lead us to choose this novel eductor. It indeed has the ability to mix the mixed liquor, biomass, and the air and generate high liquid and air velocities next to the membrane. This study examines the performance of a submerged flat-sheet MBR coupled with a Venturi-eductor to treat real municipal wastewater both in terms of fouling prevention and nutrient removal.

2. Materials and methods

2.1. Experimental design

The schematic diagrams of the experimental setup are shown in Fig. 1(a), (b), (c), and (d). The MBR tank was rectangular in shape, made up of transparent polyacrylic sheet with an effective volume of 75 L (0; Fig. 1(a)). A flat-sheet membrane (Microdyn Nadir, module Biocel Lab) of 0.34 m^2 surface area with an average 0.04 µm of pore size (1; Fig. 1(a)) was immersed inside the tank (also assembled as in Fig. 1(b)). The membrane unit was equipped with an in-built diffuser (2; Fig. 1(a)) to aerate the membrane with compressed air from the central compression unit (3; Fig. 1(a)). The cross-section of the membrane module indicating the position of the diffuser is shown in Fig. 1(c). The rate of air flow and the inlet air pressure were measured by a rotameter (Platon NG series) (4a; Fig. 1(a)) and a pressure gauge (5; Fig. 1(a)), respectively. A motor with pump head (Easyload II BT100-2 J, 77200-60) (6; Fig. 1(a)) was installed for permeation and back-washing. The motor was controlled by a frequency controller (Shenzhen Encom electric technologies Co., Ltd, ENC, EDS 800 series) (7a; Fig. 1(a)). The treated permeate was stored in a 15-L volume permeate storage tank (8; Fig. 1(a)). Two check valve connected liquid flow meters (Platon NG series) (4b and 4c; Fig. 1(a)) were connected to the pipeline of the permeate/back-washing tube to measure the permeate and the back-washing flow. A pressure transducer (−1 to +1 bar; Fox Con USA, CSPT-300F) (9; Fig. 1(a)) was installed which continuously measured the transmembrane pressure (TMP) and was connected to the computer (10; Fig. 1(a)) via a data interfacing device (ADAM 4017) (11; Fig. 1(a)). A dissolved oxygen (DO) meter (YSI Environmental) (12; Fig. 1(a)) was immersed in the tank which continuously monitored the DO concentration in the reactor. The domestic wastewater was supplied from the nearby caravans of SdeBoqer Campus of Ben-Gurion University of the Negev, Israel, and was pumped into a settling tank placed on the roof of the laboratory. The wastewater passed through another sedimentation tank and stored in a feed tank (13; Fig. 1(a)) and then finally flowed into the MBR by gravity through a float switch (14; Fig. 1(a)),which controlled the liquid volume inside the tank constant. A thermostat (Haqos aquarium) (15; Fig. 1(a)) was also immersed into the reactor to maintain the reactor's temperature at 26 ± 2˚C throughout the experiment. During the eductor mode of operation the in-built diffuser was replaced with an eductor (Spraying Systems Co.) (16; Fig. 1(a)) coupled with a one end closed perforated tube (with baffles inside) (17; Fig. 1(a)) to channelize the bubbles uniformly along the surface of the membrane. A liquid jet was formed by injecting mixed liquor by a centrifugal pump (Pan World, 250PS-3) (18; Fig. 1(a)) through the eductor. The centrifugal pump was controlled by another frequency controller (7b; Fig. 1(a)) of the same model mentioned above. The rate of mixed liquor recirculation was measured by ultrasonic sensors (Dalian Hipeak, UIL-100 M-S2) (19; Fig. 1(a)) which was connected to a digital display unit (UIL-100 M-S2) (20a; Fig. 1(a)). A pressure gauge (21; Fig. 1(a)) was installed at the mixed liquor recirculation path to measure the inlet pressure of the mixed liquor into the eductor. The atmospheric air was the automatically drawn into the liquid jet through an air inlet tube (22; Fig. 1(a)) due to the local pressure drop

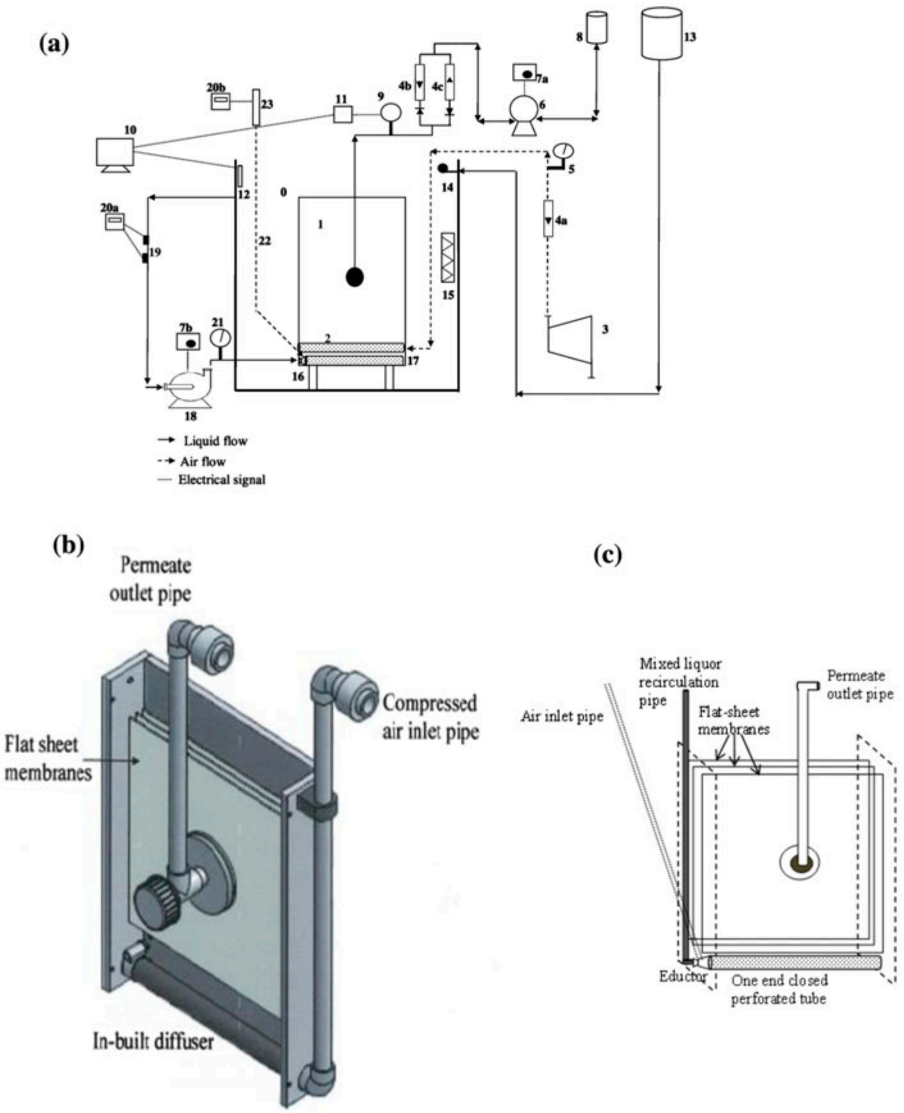

Fig. 1. (a) Schematic diagram of the experimental setup, (b) view of the membrane module with the front panel removed showing the position of the inbuilt diffuser and membranes, and (c) schematic diagram of the membrane unit with the front panel removed showing the position of the eductor and the perforated tube below the membrane elements.

at the throat of the eductor. The atmospheric air suction rate was measured by a hot wire probe anemometer (GMH-Honsberg, Labo-FG-I00500K100PS) (23; Fig. 1(a)) and was connected with a digital display device (20b; Fig. 1(a)) (BEST Electrical and Automation).

The mixing eductor used for the air injector was a nominal 1/4 inch eductor (Spraying Systems Co., Wheaton, USA) (Fig. 2(a)). The external diameter, orifice internal diameter, and the length of the eductor were 32, 5, and 76 mm, respectively. The eductor was modified (as per the guidelines of the patent) with a polypropylene tube (external diameter of 6 mm and internal diameter of 3.5 mm) inserted into the eductor to serve as an air inlet. The outlet of the air inlet tube inside the eductor was at the center of the throat of the eductor, (7.5 mm in length, 15 mm internal diameter) at an angle of 45° (Fig. 2(b)). The company specification for the eductor's performance in terms of mixing (without air inlet) is given in Table 1.

Table 1 shows that the resulting liquid flow through the eductor is much higher than the inlet liquid flow to the eductor. The eductor was placed horizontally beneath the same membrane unit after all the studies were completed with the in-built diffuser attached to that membrane unit, in order to conduct a

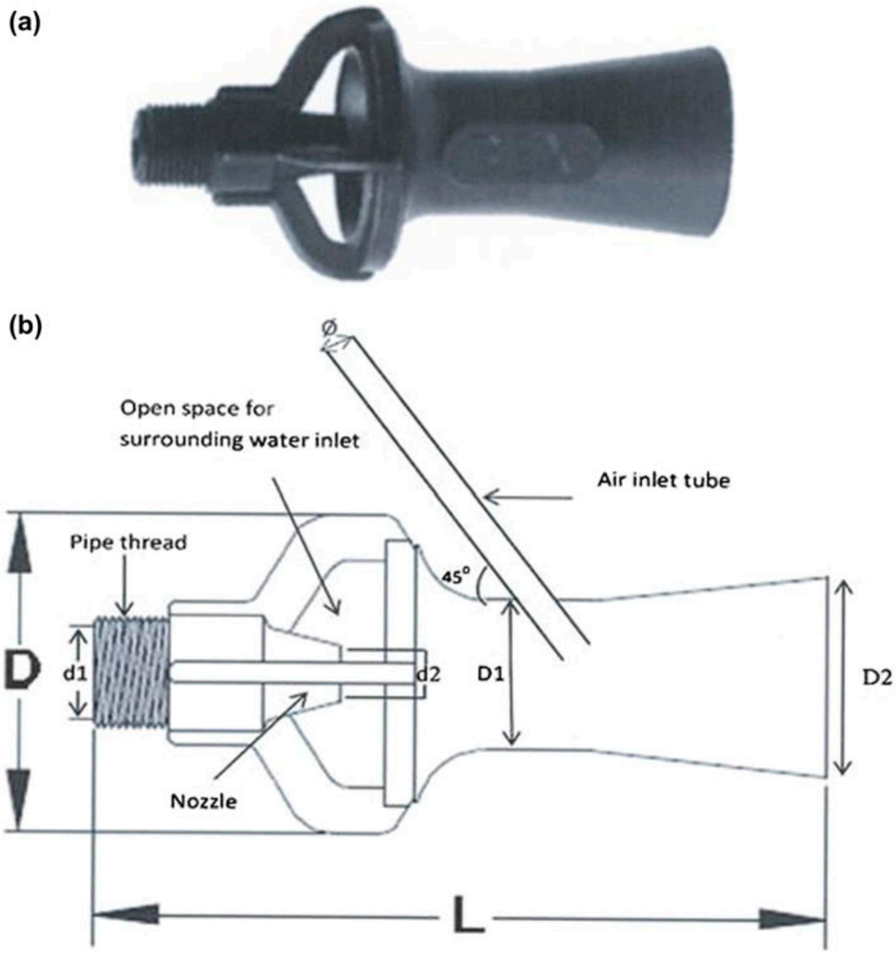

Fig. 2. (a) The mixing eductor in its original form and (b) schematic diagram of the eductor.
Notes: D (Diameter): 32 mm, d1 (orifice internal diameter): 9 mm, d2 (eductor jet inner diameter): 5 mm, D1 (internal diameter of the throat): 15 mm, D2 (internal diameter of the outlet): 18 mm, L (length): 76 mm, Ø (internal diameter of the air inlet tube (3.5 mm).

Table 1
Performance data of the mixing eductor [14]

		Inlet liquid pressure (bar)							
Nozzle no.	Flow rate (L/min)	0.5	1	1.5	2	2.5	3	3.5	4
46,550-1/4	Inlet flow rate	11.3	16	19.3	23	25	28	30	32
	Total circulation rate	53.5	75	91.5	107	118	130	140	150

comparative study between the performance of the diffuser and the eductor under almost same operating conditions. A one end closed perforated tube (with baffles inside) with 1-mm diameter holes, was placed at the mouth of the eductor to channelize the mixture of the mixed liquor and the bubbles uniformly throughout the membrane (Fig. 1(d)).

2.2. Operation of the MBR

The activated sludge was collected from the municipal wastewater treatment plant from Yeroham, Israel. The activated sludge was poured inside the MBR and was acclimated with the existing domestic wastewater in a constant permeation-backwashing mode of operation (10 min permeation and 30 s backwash) at a hydraulic residence time (HRT) of 12 h with 5 LPM of aeration (through the diffuser). The back-washing was done at a flow rate of 150 ml/min.

After the completion of the acclimatization of the reactor further experiments were started. The experimental protocol was divided into two main segments, namely, (1) operation with the in-built diffuser and (2) operation with the eductor, to have a clear idea of the difference in the performance between these two. The specific studies at each of the above-mentioned segments included (i) aeration and oxygenation study, (ii) membrane fouling study, and (iii) study of wastewater treatment efficiency. The aeration and oxygenation studies were further divided into two segments, namely (a) study of the rate of air drawn through the eductor at different mixed liquor recirculation flow at a depth of 40 cm (this was a specific study only for the eductor mode of operation), and (b) the study of oxygen transfer rate (in clean water) with both the eductor and the diffuser. The average MLSS concentration was kept around 5.5–6.5 g/L throughout the study. The experiments were first started with the diffuser mode of operation and when all the above-mentioned studies were completed we switched to the eductor mode of operation. The aeration rate was fixed at 5 LPM (as per the specification of Microdyn Nadir Company) both with the diffuser and the eductor.

The overall oxygen transfer rate (K_La) in clean water was obtained by a chemical method. First, the DO level in the reactor was reduced to zero by stoichiometrically adding (Na_2SO_3) in the tank. Cobalt chloride ($COC1_2$) was added as a catalyst. The increase in the DO with time was then measured by a DO probe (YSI environmental). The overall oxygen transfer rate (K_La) was calculated from the slope of a plot of $\ln(C_s - C_t)$ vs. t, where C_s is saturation concentration of DO and C_t is the DO at time t [11].

The membrane fouling study (for both the diffuser and the eductor mode of operation) was conducted taking 400 mbar of TMP as the threshold limit (as specified by the Microdyn Nadir Company). The MBR was operated in a continuous mode of operation (without back-washing) during membrane fouling study. The MBR was run at different fluxes (18.35, 22.1, 28.24, and 36.70 L/m^2/h) and the time it took to reach to the threshold value of 400 mbar was considered as the indicator of the membrane fouling. Every time the TMP reached to 400 mbar, the membrane was taken out of the tank and was dipped in a NaOCl–NaOH solution followed by citric acid solution for 3–4 h. Then the membrane was cleaned with the fresh water and was immersed inside the tank for the next study.

After that the performance of the MBR in terms of COD and ammonia removals at different HRTs were studied. During this phase the MBR was operated in a permeation (5 min) and backwashing (30 s, 150 ml/min) mode of operation followed by a pause (10 s) in between. At every HRT, the MBR was run for 5 d at steady-state condition and the average value for influent and effluent COD and NH_4-N were considered during data representation for this study.

2.3. Analytical methods

The pH, COD, NH_4-N, and the MLSS concentration were measured as per APHA standard methods [15].

3. Results and discussion

3.1. Aeration and oxygenation study

3.1.1. Air inlet at different mixed liquor recirculation rate through the eductor

The air inlet rates were measured through the eductor at different mixed liquor recirculation rates at a depth of 40 cm (just beneath the membrane unit) of the water level (Fig. 3). It was observed that the mixed liquor flow of 12.6 LPM (inlet pressure 0.7 bars) was required to recirculate through the eductor at a depth of 40 cm, to draw 5 LPM of air from the atmosphere. Further, it is noted that at higher rate of wastewater recirculation (recirculation rate = 14.8 LPM, inlet pressure = 1 bar) the rate of air inlet was found to be increased (10 LPM), so an increase of 2.2 LPM in water flow, resulted in an increase of 5 LPM in air flow rate. This suggests that there is a threshold liquid flow rate required to put the eductor into proper operation, and that the inlet static pressure head of the water also plays a significant role in the net air suction rate. Since our experimental setup was a lab-scale setup with a small unit of MBR (tank volume = 75 L, membrane surface area = 0.34 m^2) and the Microdyn Nadir's recommended aeration rate was 5 LPM, we were limited to conduct our studies in the relatively less efficient zone of the eductor's operation.

3.1.2. Oxygen transfer rate study

After that the oxygen transfer rates were studied both with the diffuser and the eductor in clean water. The slope of a curve of $\ln(C_s - C_t)$ vs. t showed the K_La values of both the eductor and the diffuser which were converted to the standard temprature as per Eq. (1) [16]:

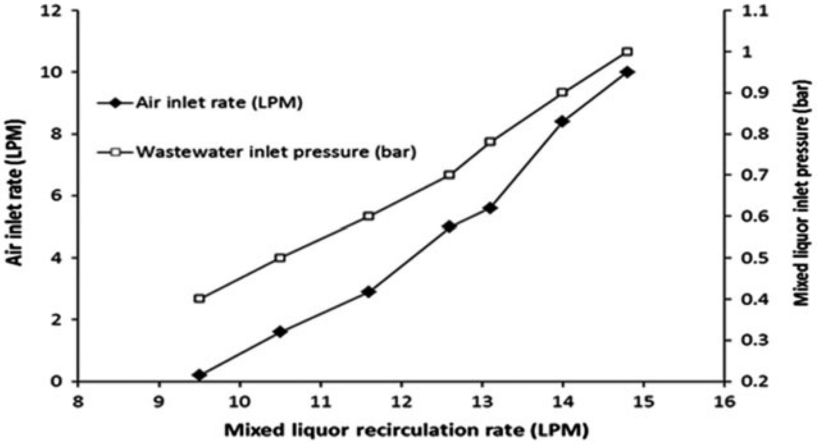

Fig. 3. Air inlet rates at different mixed liquor recirculation flow and inlet pressures at a depth of 40 cm.

$$K_La_{(T)} = K_La_{(20^\circ C)} \times 1.024^{(T-20)} \quad (1)$$

The K_La value at 20℃ with the eductor was found to be much more (18.49/h) than the diffuser (5.6/h). Fig. 4 shows the time differences between the eductor and the diffuser to reach to oxygen saturation level. The better oxygen transfer rate of the eductor over the diffuser in the above-mentioned observations could be explained with the fact that a high degree of mixing between water and air took place at the throat of the eductor forming a mixed jet of air and water which came out from the perforated tube (to the bulk liquid), placed at the mouth of the eductor.

3.2. Study of the membrane fouling

The membrane fouling was studied at different fluxes (18.35, 22.1, 28.24, and 36.70 L/m^2/h) and the rate of TMP increase with time was recorded. It was observed that at every flux the time taken to reach 400 mbar TMP for the diffuser-operated MBR was lower than that of the eductor-operated MBR (Fig. 5(a), (b), (c), and (d)). This was a clear evidence of the better membrane fouling control efficiency of the eductor compared to the diffuser. This might be due to the combined high velocities of the liquid and the air by the eductor which resulted in the generation of high mixing and the high share force across the membrane surface, which led to better fouling control compared to the diffuser. Moreover, apparently larger sized air bubbles were generated through the perforated distribution tube (1-mm diameter holes) placed at the mouth of the eductor, when compared to the bubbles of the fine diffuser. This would contribute to the rising of the eductor bubbles at a higher velocity compared to the smaller bubbles generated by the diffuser. Wicaksana et al. reported that the average bubble rise velocity values using the 1-mm nozzle were slightly higher than the values using the 0.5-mm nozzle size [8]. Furthermore, in several studies, it has been widely documented that the large bubbles are more efficient in the membrane fouling control than the small bubbles [10,17,18]. It can also be seen from the Fig. 5(d) that at a higher flux (36.70 L/m^2/h), both the diffuser and the eductor took almost same time to reach the threshold TMP (400 mbar). This might be attributed to the fact that at this higher flux the rate of deposition of the fouling materials on the surface of the membrane was much higher which rendered the air–liquid flow ineffective at the given air flow rate (5 LPM). It has been well documented in the previous literatures that at high flux the aeration plays less significant role in membrane fouling control [9,10].

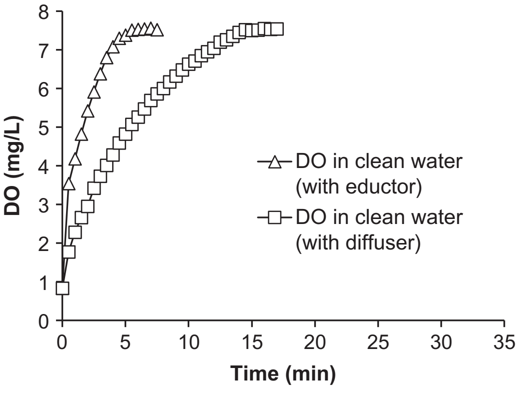

Fig. 4. Rise of DO with time with both the eductor and the diffuser.

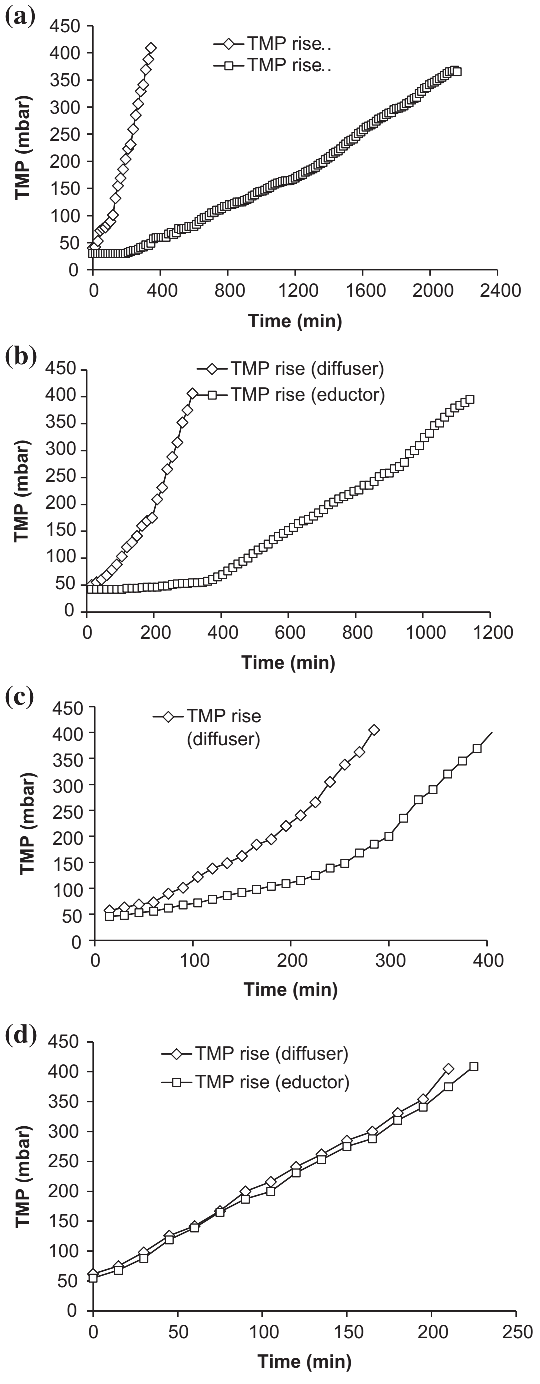

Fig. 5. (a) TMP increase with time at an initial flux of 18.35 L/m^2/h, (b) TMP increase with time at an initial flux of 22.1 L/m^2/h, (c) TMP increase with time at an initial flux of 28.24 L/m^2/h, and (d) TMP increase with time at an initial flux of 36.7 L/m^2/h.

3.3. Performance of the MBR at different HRTs

After the completion of the membrane fouling study the performance of the MBR (both with the nozzle and eductor) at different HRTs (12, 10, 8, and 6 h) in terms of COD and ammonia removals was carried out. Fig. 6 shows the COD and ammonia loading rates at different HRTs. Since the experiment was conducted using real wastewater, the COD and ammonia loading rates for both diffuser and eductor-operated MBR varied in a given HRT. Fig. 7 shows the performance of the MBR in terms of COD and ammonia removal.

This is clearly visible from Fig. 7 that at every HRT the MBR showed better performance in terms of COD and ammonia removals when operated with the eductor compared to the diffuser. The overall COD reduction of the MBR when operated with the eductor was found to be in the range of 93–96% at different organic loading rates, whereas the overall COD reduction was observed in the in the range of 83–91% at different organic loading rates when operated with the diffuser. This might be due to the high degree of mixing between the mixed liquor and the air with the eductor which led to better mass transfer and better contact between the wastewater and air with the micro-organisms compared to the diffuser. This is consistent with the previous study which reported improved performance of MHCR equipped with Venturi-type aeration nozzles [11].

Whereas, not much improvement was observed in terms of ammonia removal with the eductor (in the range of 67–77%) over the diffuser (in the range of 62–75%). This could be because of the development of a very low DO region (DO < 0.5 mg/L) at the bottom of the MBR tank with both the eductor and the diffuser which might have reduced the oxidation of ammonia. The reason for low DO at the bottom could be due to the fact that highly oxygenated water was pulled through the regions of high biomass as it moved from high concentration mixing above the diffuser or

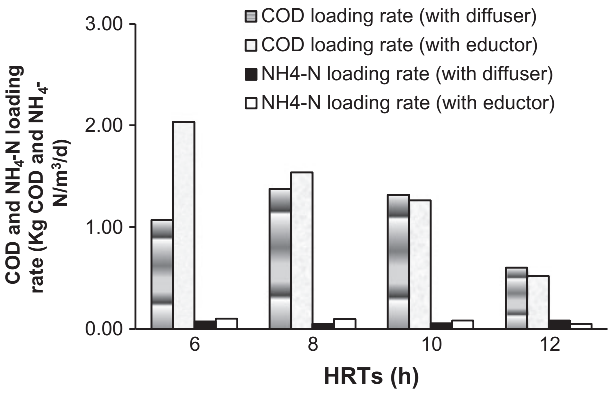

Fig. 6. COD and NH$_4$-N loading rates at different HRTs.

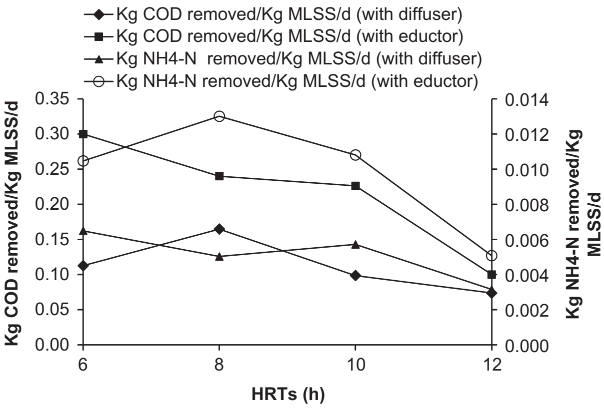

Fig. 7. COD and ammonia removals at different HRTs.

eductor and then on the outside of this region. In these regions, there could be high rate of oxygen uptake and minimal addition of additional oxygen to water and thus the DO dropped to low levels.

The above-mentioned observations suggest that improved efficiency in terms of membrane fouling mitigation and nutrients removal can be achieved by operating the MBR with eductor instead of diffuser. Such an improvement in membrane fouling mitigation may lead to less frequent chemical cleaning and/or replacement of expensive membrane filters, which would lead to the reduction of the cost of operation. Further, increased air entrainment within the mixed liquor may be realized, as suggested by Fig. 3 when greater than 5 L/min of air is permitted to be drawn into eductor. Accordingly, improved efficiency may be realized for larger MBR systems when inlet of air through eductor is unrestricted. Not only that, the eductor-based MBR would reduce its footprint by providing the dual advantages of mixing as well as aerating the MBR unit using a single device. Our experiment was a prototype for the evaluation of the feasibility of the application of this novel eductor for the treatment of wastewater in MBR. The large-scale application of the eductor as an alternative and efficient means of wastewater treatment in MBR will be studied in the future.

4. Conclusion

The flat-sheet membrane MBR coupled with an eductor proved to be very efficient in terms of overall oxygen transfer rate, membrane fouling control, and the treatment of wastewater. The following conclusions can be made from the present study:

(a) The aeration through eductor showed a high rate of oxygen transfer in clean water compared to the diffuser.
(b) The membrane fouling rate was found to be much less up to a flux of 28.24 L/m^2/h with the eductor compared to the diffuser. Further increment in the flux led high rates of membrane fouling in both the cases.
(c) The treatability of wastewater in terms of COD reduction at every HRT was also found to be much higher with the eductor compared to the diffuser, whereas, the ammonia removal with both the eductor (in the range of 67–77%) and the diffuser (in the range of 62–75%) at different HRTs was found to be more or less the same.

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