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Process Analysis and Optimization of Industrial Estate Wastewater Treatment Using Conventional and Compartmentalized Membrane Bioreactor: A Comparative Study

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Abstract: Membrane bioreactor (MBR) technology isan integrated combined system ofbiological and membrane processes to treat wastewater. MBR competently removes organic mattersand suspended solids from any type of wastewater. This study is aimed to evaluate and compare the performance of conventional and compartmentalized lab-scale MBR in treating an industrial estate wastewater (Faraman Industrial Estate, Kermanshah, Iran). The MBR systems were operated in two conditions; one in a completely stirred regime(conventional activated sludge (AS) system) and the other one in a semi plug flow regime(compartmentalized activated sludge (CAS) system). Experimental design was performed by response surface methodology (RSM) to assess the effect of two independent numerical factors *i.e.* hydraulic retention time (HRT) and mixed liquor volatile suspended solids (MLVSS) on nine responses.From the overall results, it was found that CAS-MBR performed better than AS-MBR.The CAS-MBR achieved 94.9% of TCOD removal efficiency at 24 h of HRT and MLVSS concentration of 10000 mg.L^{-1}. Compared to AS-MBR, CAS-MBR showed higher percentage of removal efficiency for total nitrogen andtotal Kjeldahl nitrogen. Moreover, CAS-MBR recorded the lowest SVI value of 55 mL.mg $^{-1}$compared to AS-MBR. Additional microfiltration has increased the TCOD removal in both systems. As a conclusion, the CAS-MBR operated at the same condition showed higher treatment capacityin compare to AS-MBR.

Key words: Industrial estate wastewater treatment · Conventional and compartmentalized MBR · Response surface methodology (RSM)

INTRODUCTION

As industries are rapidly developing, various kinds of wastewater discharged from the plants include high concentration organics and nutrients. The composition of industrial effluents is characterized by the high structural diversity of constituents and their high concentration level. Industrial wastewaters may be a severe hazard to receive waters and their plants and fauna. One of the major problems associated with the biological treatment of industrial wastewater is its slow and non-biodegradable fraction of chemical oxygen demand (COD) which inhibits the treatment performance of the bioreactors. Biological oxygen demand (BOD_5) per COD ratio (BOD_5/COD) constitutes a good measurement of the biodegradability of a wastewater and contaminants with a ratio of BOD_5/COD =0.4 are generally accepted as biodegradable [1]. From a review, the BOD_5/COD ratio for industrial estate wastewaters is varied from 0.17 to 0.74 [2]. Therefore, industries should attempt to treat its wastewater that will yield a satisfactory effluent for the particular receiving stream, which may necessitate considerable study, research and pilot investigations. The composition of industrial effluents is characterized by diverse in constituents with high concentration level [3]. High strength municipal wastewater [4] and complex composition of the industrial wastewater [5] accounts for, in some cases, unpredictable toxicological and ecotoxicological effects. In addition, slowly biodegradable chemical oxygen demand (sbCOD) is the major problem

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Table 1: Summary of results from MBR studies on wastewater reuse

No.	Objective	MBR system details	MBR effluent quality	Ref.
1	Comparison of the performance of direct membrane filtration and MBR systems for municipal wastewater	MLSS: 4000–7000 mg/L Submerged hollow fibers Pore size:0.1 µm	COD_c: < 9 mg/L TSS: < 0.3 mg/L Turbidity: < 0.1 NTU	[15]
2	Effect of MLSS and organic loading rate on system performance for synthetic wastewater	MLSS: 3000–15000 mg/L Submerged tubular Pore size:20–40 µm	COD_c: 18–224 mg/L TSS: 0 mg/L	[16]
3	Effectiveness of MBR at COD and N removal at different HRTs for municipal wastewater	MLSS: 4200 – 8700 mg/L Flat sheet Pore size:0.45 µm	COD: 94–97% removal TSS: 100% removal TN: 62–76% removal	[17]
4	Effects of high MLVSS, sludge age and bioreactor configuration on MBR treating municipal wastewater	MLSS: 5000–15000 mg/L Submerged hollow fiber Pore size: 0.1 µm	COD: 96% removal TSS: 100% removal TN: 36–80% removal	[18]
5	Feasibility of MBR application in wastewater reuse for municipal wastewater	MLSS: 4800–9000 mg/L Submerged hollow fibers Pore size:0.04 µm	COD_c: 4–11 mg/L TSS: 0 mg/L TN: 1.1–5.4 mg/L	[19]
6	Influence of activated sludge characteristics on membrane fouling in a hybrid membrane bioreactor	MLSS: 12000 mg/L Submerged hollow fiber Pore size: 0.04 µm	COD_c: 12.9±3 mg/L TN: 8.1±4.5 mg/L Turbidity: <1 NTU	[20]
7	Effect of SRT and MLSS on performance of an MBR treating municipal wastewater	MLSS: 4000–17000 mg/L Submerged hollow fiber Pore size: 0.02 µm	COD_c: 19–40 mg/L TSS: 0 mg/L TN: 6.2–13.3 mg/L	[21]
8	Effects of operating parameters on MBR performance with respect to the removal of persistent organic pollutants	MLSS: 200 – 430 mg/L Flat sheet Pore size:0.4 µm	COD_c: 2.5–31 mg/L Turbidity: 0.2 NTU	[22]

associated with industrial wastewaters that are not typically considered in conventional treatment processes design. One solution for the aforementioned problem is to develop a bio process with high biomass concentration to provide a competitive microbial media.

Response surface methodology (RSM) is a combination of mathematical and statistical techniques used for developing, improving and optimizing the processes and it is used to evaluate the relative significance of several factors even in the presence of complex interactions. This methodology is widely used in chemical engineering, notably to optimize process variables. Optimization of biological treatment of industrial estate wastewater in a sequence batch reactor (SBR) [6], analysis of the interactive effects of cell concentration and light intensity on hydrogen production by *Rhodopseudomonas capsulate* [7]. Optimization of medium for phenylalanine ammonia lyase production in *Escherichia coli* [8], acidogenesis of cheese-whey wastewater to acetic and butyric acids [9], powdered activated carbon augmented activated sludge process for treatment of semi-aerobic landfill leachate [10], Fenton and photo-fenton treatment of distillery effluent and optimization of treatment conditions [11], process modeling and analysis of palm oil mill effluent treatment in an up-flow anaerobic sludge fixed film bioreactor [12], for optimization of electrospunnanofiber formation process [13], process modeling and analysis of biological nutrients removal in an integrated RBC-AS system using response surface methodology [14] are the examples of the RSM applications.

Membrane bioreactor (MBR) technology, which combines biological-activated sludge and membrane processes. For the treatment of many types of wastewaters, filtration has become more popular, abundant and accepted in recent years. Conventional activated sludge (CAS) process cannot cope with either composition of wastewater or fluctuations of wastewater flow rate. MBR technology is also used in cases where demand on the quality of effluent exceeds the capability of CAS. Although MBR capital and operational costs exceed the costs of conventional process, it seems that the upgrade of conventional process occurs even in cases when conventional treatment works well. Use of MBRs for wastewater reuse applications is still in its infancy and research teams worldwide are focusing their attention on characterizing the performance of MBRs for wastewater reuse and developing approaches to optimize the treatment efficacy. Table 1 summarizes the results from some recent studies on the use of MBRs for wastewater reuse applications.

The focus of the present study is to evaluate the performance of two types of lab-scale membrane bioreactors (MBR) in treating Faraman industrial wastewater (FIW). The MBR systems were operated in a completely stirred activated sludge (AS-MBR) and a semi plug flow compartmentalized activated sludge (CAS-MBR). For both systems, the output was analysed based on the interactive effect of two process variables *i.e.*mixed liquor volatile suspended solids (MLVSS) concentration and hydraulic retention time (HRT). Nine main parameters *i.e.* total chemical oxygen demand (TCOD) removal, rapid biodegradable chemical oxygen demand (rbCOD) removal, slowly biodegradable COD (sbCOD) removal, total effluent nitrate (NO_3^-) (TEN) concentration, total kjeldahl nitrogen (TKN) removal, total nitrogen (TN) removal, total phosphorous (TP) removal, sludge volume index (SVI) and effluent turbidity were measured and calculated as process responses. Response surface methodology (RSM) was used to analyse the collecteddata. Finally the process parameters were optimized.

MATERIALS AND METHODS

Wastewater Characteristics: Untreated wastewater samples were taken from Faraman Industrial Zone, Kermanshah, Iran. Table 2 shows the characteristics of this wastewater. The samples were stored in a cold room (4°C) before use and this step had no observable effect on its composition. Different dilutions of Faraman industrial wastewater (FIW) were prepared using tap water. Supplementary nutrients such as nitrogen (NH_4Cl) and phosphorous (KH_2PO_4) were added to give a ratio of COD: N: P of 1000:50:20.

Table 2: Faraman Industrial wastewater (FIW) characteristics

Parameter	Unit	Range
TCOD	$mg.L^{-1}$	800-1600
BOD_5	$mg.L^{-1}$	220-500
$nbCOD^*$	$mg.L^{-1}$	35
sbCOD	$mg.L^{-1}$	450-750
TN	$mg.L^{-1}$	200-300
TP	$mg.L^{-1}$	40-60
TSS	$mg.L^{-1}$	100-400
pH	-	7.0-7.6

*The nbCOD was anticipated to be about 35 mg/l as intercept of (effluent COD) versus (1/HRT) plot.

Bioreactor Configuration and Start up: Figs. 1a and 1b illustrate the schematic drawings of lab-scale AS-MBR and CAS-MBR bioreactor set-up, respectively. Both set-ups have three basic vessels, *i.e.* an aeration tank, a settling tank and a membrane chamber. The working volume of the aeration tank in both systems was 3030±15 mL. The membrane chamber's working volume was 4150±15 mL cylindrical vessel including a submerged metallic membrane holder as shown in Fig. 2. Two units of

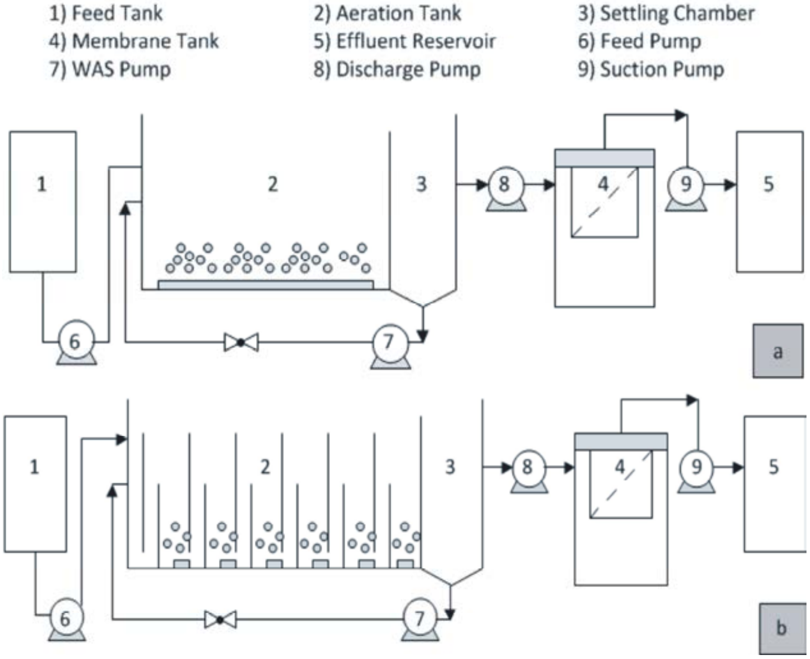

Fig. 1: Schematic diagram of (a) AS-MBR set-up and (b) CAS-MBR set-up.

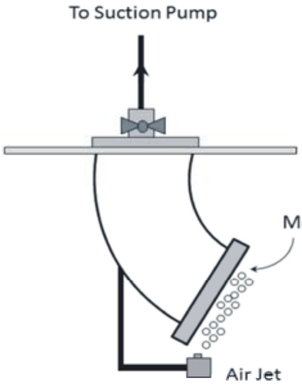

Fig. 2: Submerged membrane holder

Table 3: Experimental conditions.

Type of bioreactor	Run No.	MLVSS (B) (mg.L-^{1})	HRT (A) (h)
AS-MBR	1	4000	4
	2		8
	3		12
	4		36
	5	6000	24
	6	8000	18
	7		24
			24
			24
			24
			24
	8		30
	9	10000	24
	10	12000	4
	11		12
	12		36
CAS-MBR	1	4000	4
	2		8
	3		12
	4		36
	5	6000	24
	6	8000	18
	7		24
			24
			24
			24
			24
	8		30
	9	10000	24
	10	12000	4
	11		12
	12		36

adjustable speed peristaltic pump (PD5201, Heidolph, Germany) were used to feed and apply trans-membrane pressure to the membrane tanks. In order to control the dissolved oxygen (DO) level in aeration tank, DO was monitored in all experiments.

To start up the systems, the reactor was continuously fedby FIWwith 1.0 g COD.L^{-1}d^{-1} of initial organic loading rate (OLR) for 24 h of HRT. The HRT and OLR were maintained constantly for 7 days throughout the start-up procedure. During this period, COD and BOD reduction were monitored.

Experimental Design and Mathematical Model

Variables: A general factorial design of RSM was used in this study. The design involves one categorical factor *i.e.* type of hydraulic regime (AS-MBR and CAS-MBR) and two different numerical factors *i.e* HRT (12-36h at 7 levels) and MLVSS (4000-12000 mg.L^{-1} at 5 levels). The range was selected based on preliminary studies.

Design of Experiments: The biological treatment process was evaluated based on the number of experiments suggested by the factorial design as shown in Table 3. A total of 32 experiments were designed with 8 replicates to verify the results and errors. Due to industrial characteristics of FIW, rbCOD and sb CODfractionations were also monitored throughout the experiments. Therefore, total of nine parameters were identified as the responses. Following are the parameters; TCOD removal,rbCOD removal, sbCOD removal,TEN concentrations, TKN removal, TN removal, TP removal, SVI and effluent turbidity. Design of experiment (DOE) statistically minimizes the number of experimentsand eliminates experimental errors systematically.

Mathematical Modeling: After conducting the experiments, the coefficients of the polynomial model were calculated using the following equation [23].

$$R = \beta_0 + \sum \beta_i X_i + \sum \beta_{ij} X_i X_j + \sum \beta_{11} X_1^2 + \varepsilon$$

where R is the response,β_0 is the constant term, β_i representsthe coefficients of the linear parameters, β_{ii} represents the coefficients of the quadratic parameter, β_{ij}represents the coefficients of the interaction parameters X_i and X_j and i < j, X_i and X_j represents the variablesand åis the random error or noise to the response. The results were completely analyzed using analysis of variance (ANOVA) automatically performed by Design Expert software (Stat-Ease Inc., version 7.0.0). The Design Expert software is a windows-compatible software which provides efficient design of experiments for the identification of vital factors that affect the process and uses response surface methodology (RSM) to determine optimal operational conditions. The results can be obtained as 3D presentations for visualization and also as contours to study the effect of system variables on responses. From these three-dimensional plots, the simultaneous interaction of the two factors on the responses was studied. The optimum region was also identified based on the main parameters in the overlay plot.

Analytical Methods: The concentrations of TCOD, BOD and TEN, the removal of TKN, TN and TP, SVIand MLVSS of the systems were determined using standard methods for water and wastewater testing [24]. For COD, a colorimetric method with closed reflux procedure was used. To measure the absorbance of COD samples, a spectrophotometer (model 6320D, Jenway, USA) at 600 nm was used. TKN was determined using TKN meter Gerhardt (model Vapodest10) and the turbidity was measured usingturbidimeter (model 2100P, Hach Co.).

RESULTS AND DISCUSSION

Statistical Analysis: The ANOVA results for the responses are summarized in Table 4. In this study, various responses were investigated; therefore, different degree of polynomial models was used for data fitting. The regression equations obtained are presented in Table 4. In order to quantify the curvature effects, the data from the experimental results were fitted to higher degree polynomial equations, *i.e.* two-factor interaction (2FI) and quadratic. The model terms in the equations are generated after eliminating the insignificant variables. Based on the statistical analysis, the models were highly significant with very low probability values (<0.0010). Table 4 shows that the model terms of independent variables were significant at the 95% confidence level. The square of correlation coefficient for each response was computed as coefficient of determination (R^2). It showed a good agreement between actual and predicted values.

Adequate precision (AP) is a measurement in a certain range to predict response relative to its associated error or, in other words, a signal-to-noise ratio. The values of AP should be 4.00 or more [23]. Table 4 shows that th values of AP for all the models were satisfactory. Conversely, low values of the coefficient of variation (CV) (1.74-12.96%) indicates good precision and reliability of the experiments as suggested by Kuehl and Khuri and Cornell [23-26].

AS-MBR and CAS-MBR Performance CODRemoval: COD removal for both systems were quantified using three different parameters *i.e.* TCOD,rbCOD and sbCOD. Due to industrial characteristics of FIW, rapid (rbCOD) and slow (sbCOD) biodegradable COD fractionations were also monitored throughout the experiments.

TCOD Removal: Two modified quadratic models were developed to describe the variation of the TCOD removal efficiency as a function of the variables (HRT=A and MLVSS=B) in both systems as shown in Table 4. The significance of each coefficient was determined by *F*-value and *P*-value. From Table 4, it was noticed that A, B and A^2 are the significant model terms for the both systems. Figs. 3a and 3b illustrate the effects HRT and

Table 4: ANOVA results for the responses studied

Type of bioreactor	Response	Modified equations with significant terms*	Probability	R^2	Adj.R^2	Adeq. Precision	S.D	CV
AS-MBR	TCOD removal	$88.21+8.41A+3.46B-11.98A^2$	0.0008	0.7415	0.6769	9.898	5.44	6.49
	Effluent NO_3^-	$35.45+0.84A+5.56B-5.42B^2-0.86AB$	< 0.0001	0.9877	0.9816	38.860	0.59	1.74
	TKN removal	$14.96+1.31A+5.05B$	< 0.0001	0.8529	0.8234	18.215	1.45	9.71
	TP removal	$10.86+1.84A+2.82B-1.65B^2-0.90AB$	< 0.0001	0.9888	0.9832	51.105	0.29	2.86
	SVI	$106.97-53.92B+20.65B^2$	< 0.0001	0.9305	0.9166	21.814	10.29	9.02
	Effluent Turbidity	$7.84-0.53A-6.94B+2.21A^2+3.05B^2$	< 0.0001	0.9885	0.9843	39.745	0.71	6.78
CAS-MBR	TCOD removal	$89.21+7.29A+8.22B-9A^2$	< 0.0001	0.8182	0.7727	13.150	4.72	5.51
	Effluent NO_3^-	$34.67+1.23A+5.94B-4.93B^2$	< 0.0001	0.9594	0.9459	24.964	1.03	3.14
	TKN removal	$15.38+7.03B$	< 0.0001	0.8678	0.8558	20.425	1.75	11.41
	TP removal	$10.28+1.84A+2.82B-0.90AB$	0.0002	0.8765	0.8353	18.231	0.92	8.97
	SVI	$107.69+2.54A-58.74B+8.24B^2$	< 0.0001	0.9972	0.9962	99.478	2.22	2.01
	Effluent Turbidity	$7.45-5.96B+3.05B^2$	< 0.0001	0.9443	0.9357	22.947	1.20	12.96

* A and B are HRT and MLVSS, respectively.

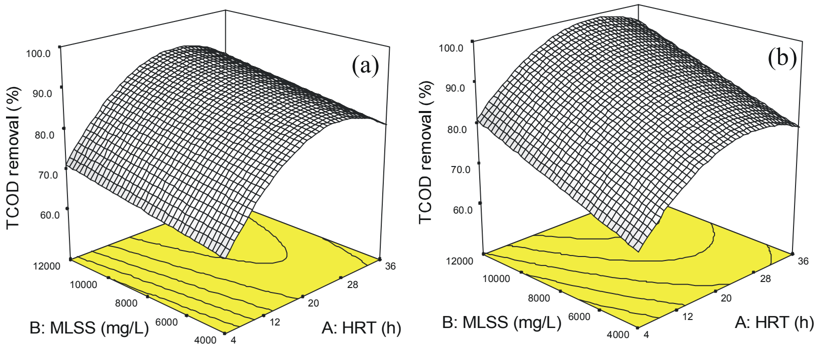

Fig. 3: Response surface plots for TCOD removal; (a) AS-MBR, (b) CAS-MBR.

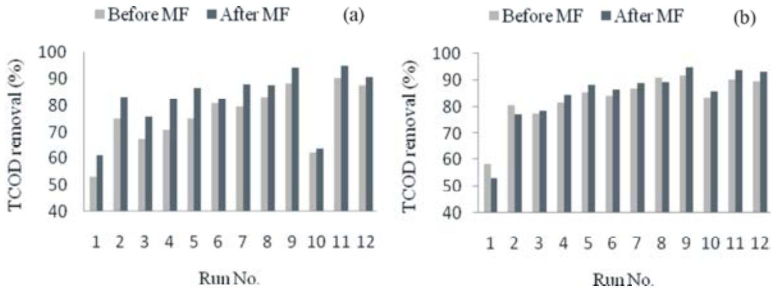

Fig. 4: Effect of microfiltration on the TCOD removal; (a) AS-MBR, (b) CAS-MBR.

MLVSS on the removal of TCOD in the AS-MBR and CAS-MBR, respectively. An increasing trend in TCOD removal percentage was observed with an increase in HRT and MLVSS concentration.

As expected, CAS-MBR system showed a better performance of TCOD removal compared to AS-MBR. Maximum TCOD removal efficiency for AS–MBR was 94.7% at HRT of 24h and MLVSS of 12000 mg.L^{-1}, while for CAS-MBR it was more than 98% at HRT of 24h and MLVSS of 12000 mg.L^{-1}. At lower HRT and MLVSS values, (4h and 4000 mg.L^{-1}), minimum removal of TCOD was recorded for both systems *i.e.* 61.0% for AS-MBR and 53.1% for CAS-MBR.

In order to analyze the performance of the biological treatment, TCOD removal measurements were also taken before and after microfiltration (MF). Figs. 4a and 4b show the effects of TCOD removal with and without membrane microfiltration in AS-MBR and CAS-MBR systems, respectively. The data have been plot according to the number of experiments in Table 3. Microfiltration showed a good improvement in TCOD removal efficiencies for both systems. It showed about 1.5 to 11.7% and 1.0 to 3.6% increase in TCOD removal for AS-MBR and CAS-MBR systems, respectively. These results prove that microfiltration enhances AS-MBR to remove its TCOD content. Therefore, the need for microfiltration in CAS-MBR is less than AS-MBR.

rbCODand sbCOD Removal: Fig. 5a shows rbCOD removal efficiencies for AS-MBR and CAS-MBR systems. Highest rbCOD removal was achieved at HRT of 20 and 12hwith the MLVSS concentration of 8000 mg.L^{-1} and 12000 mg.L^{-1} for CAS-MBR system and AS-MBR system respectively. A minimum removal of rbCOD was recorded at HRT of 4h and MLVSS concentration of 4000 mg.L^{-1} for both systems. CAS-MBR system showed higher (92%) average removal of rbCOD compared to AS-MBR (87%). This is because of the semi plug-flow regime in CAS-MBR provides additional area for reaction to take place along the reactor and it has significant low dead zone. In overall, both bioreactors showed a good performance of rbCOD removal.

One of the major problems associated with biological treatment of industrial wastewaters is non-biodegradable (nbCOD) and slow biodegradable (sbCOD) fraction of COD. Both COD's inhibit the performance of bioreactors [1]. BOD/COD ratio represents a good measurement for biodegradability of a wastewater. Contaminants with a ratio of $BOD_5/COD \geq 0.4$ are generally accepted as biodegradable [1]. The ratio of FIW was in the range of 0.22-0.35. Fig. 5b shows the removal efficiencies of sbCOD in AS-MBR and CAS-MBR systems. Atthe highest operating condition of HRT (36 h) and MLVSS concentration (12000 mg.L^{-1}), the maximum removal efficiency for AS-MBR and CAS-MBR systems were

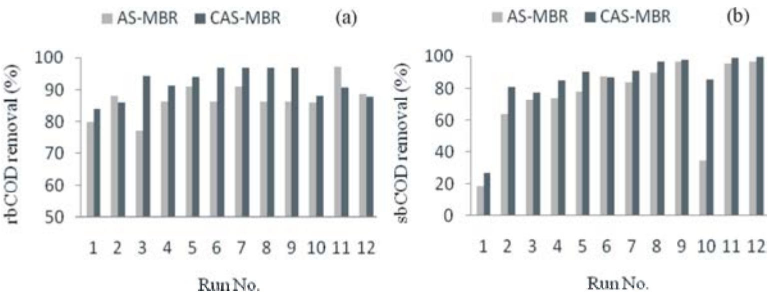

Fig. 5: Evaluation of (a) rbCOD removal and (b) sbCOD removal efficiency in the AS-MBR and CAS-MBR.

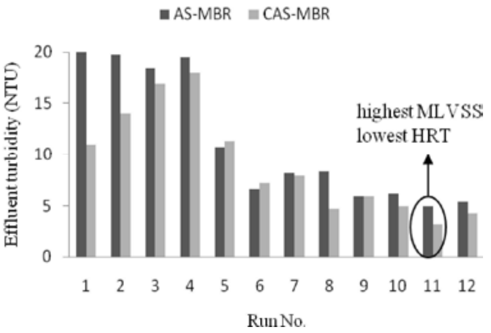

Fig. 6: Effluent turbidity under different operational conditions studied.

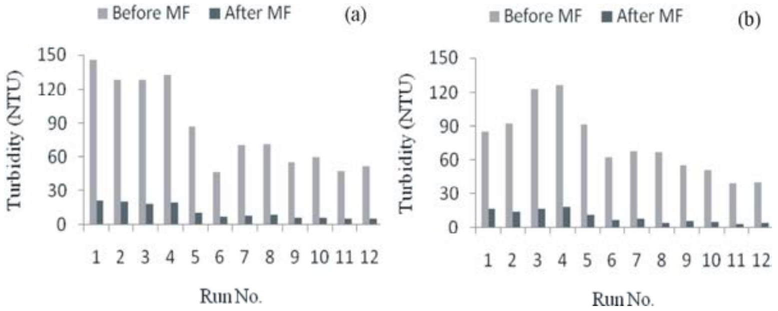

Fig. 7: Effect of microfiltration on the turbidity reduction; (a) AS-MBR, (b) CAS-MBR.

recorded as 96.6 and 99.7%, respectively. On the hand, CAS-MBR was more efficient than AS-MBR in terms of sbCOD removal and it was merely due to its specific hydraulic regime.

Effluent Turbidity: Effluent turbidity measurement is used to indicate the clarity of treated wastewater with respect to colloidal and residual particulate matter. Thus, in this study the potential of the membrane bioreactors to reduce the initial turbidity of the influent (~ 700-1000 NTU) was analyzed. Fig. 6 shows the trend of effluent turbidity for both systems according to the number of runs in Table 3.

Minimum value of turbidity was achieved at the highest MLVSS concentration (12000 mg.L^{-1}) and lowest HRT (12 h). The range of the effluent turbidity achieved was 5.0 - 21.0 NTU and 4.1 - 18.0 NTU for AS-MBR and CAS-MBR, respectively. Both systems managed to clarify the effluent efficiently. However, it was observed that at certain MLVSS concentration, if the HRT is increased there was a drastic change in turbidity for both systems. Higher values of turbidity in AS-MBR system was observed compared to CAS-MBR and this could be due to cell debris during the biological treatment.

Figs. 7a and 7b show the effect of microfiltration in turbidity reduction for AS-MBR and CAS-MBR systems. The data is presented based on the number of runs in Table 3. Microfiltration showed a significant improvement in turbidity reduction for both systems. The figures show about 84.5-89.7% and 80.0-91.8% increase in turbidity reduction for AS-MBR and CAS-MBR systems, respectively. AS-MBR and CAS-MBR (97.00-99.50 and 97.43-99.68%, respectively) have sufficiently reduced turbidity in all the experiments studied.

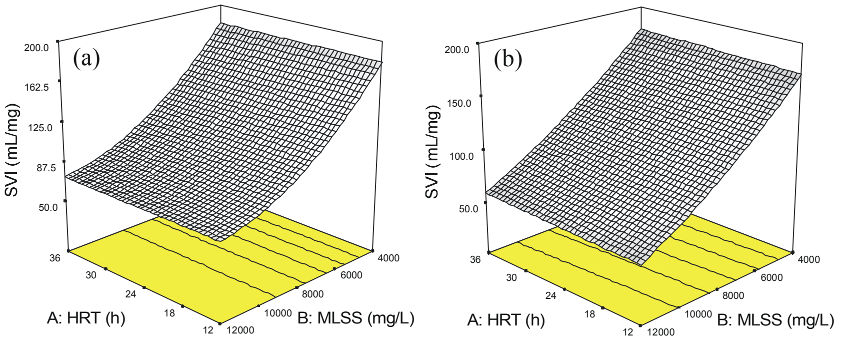

Fig. 8: Response surface plots for SVI; (a) AS-MBR, (b) CAS-MBR.

Sludge Volume Index (SVI): The SVI was reported as milliliter of settled volume per gram of MLVSS. SVI readings are used to identify the settling and compaction characteristics of sludge and determine the effects of the variables on the sludge characteristics. From the literature it is known that SVI< 80, 80≤ SVI ≥150 and SVI > 150 indicates excellent, moderate and poor settling and compacting characteristics respectively. From the ANOVA results in Table 4, the significant model terms for SVI was identified as a function of B and B^2 for AS-MBR and A, B and B ^{2}for CAS-MBR. Figs. 8a and 8b depict the dependency of SVI with variables in AS-MBR and CAS-MBR, respectively. The SVI values are in between 70.8-185 mL.mg^{-1} and 55-177.5 mL.mg^{-1} for AS-MBR and CAS-MBR, respectively.

The results also showed that for CAS-MBR, SVI decreased intensively when MLVSS concentration increases from 4000 to 12000 mg.L^{-1}, indicating favored conditions for microbial aggregation at a lower food to microorganisms (F/M) ratio [27] in the plug-flow hydraulic regime. An insignificant effect on SVI was noticed with changes in HRT for the range tested, although at certain MLVSS concentration (8000 mg.L^{-1} for run numbers 6, 7 and 8) increase in HRT led to a slight increase in the response. This could be related to excessive growth of filamentous bacteria in low F/M ratio [27].

Total Nitrogen (TN) Removal: Due to the usage of high concentrations of MLVSS and longer period of HRT in this study (12000 mg.L^{-1} and 36h, respectively), the nitrogen fractionation and phosphorus concentration were monitored to find out the probability of the biological nutrient nitrogen and phosphorus removal.

Total Effluent Nitrate (NO_3^-)(TEN) Concentration: Nitrate (NO_3-N) is the most oxidized form of nitrogen found in wastewater. In Iran, standard limit of nitrogen has been set to50 mg.L^{-1} as NO_3^- in primary drinking water becauseof its serious health effects and occasionally fatal effects on infants.

The regression results for the effluent NO_3^- data are presented in Table 4. A, B, B^2 and AB were significant model terms for the AS-MBR, while for CAS-MBR were A, B and B^2, indicating that MLVSS concentration (B) is more effective than HRT (A) on the response in the both types of hydraulic regimes. It was observed that an increase in the variables caused an increase in the responses in the both systems due to an increase in oxidation potential that favored the nitrification process [5]. Effluent NO_3^- concentration increased from 22.49 to 35.87 mg.L^{-1}and 21.35 to 35.98 mg.L^{-1} for AS-MBR and CAS-MBR, respectively. Maximum values of NO_3^- were obtained at maximum HRT and MLVSS concentration in both systems. Low F/M value at high MLVSS concentrations and low BOD loading rate at the high HRTs (≤ 0.16 g.L^{-1}.d^{-1} at HRT≥ 18h) in the AS-MBR and CAS-MBR systems resulted the high nitrification rate. A similar finding was reported by Farizoglu and his colleagues [28]. Furthermore, in this study higher dosage of dissolved oxygen (DO) was applied (5-7 mg.L^{-1}) and this could also indirectly enhances the nitrification process.

Total Kjeldahl Nitrogen (TKN) Removal: Removal of TKN is essential to control the release of organic nitrogen to the medium. The TKN removal data was fitted with two modified linear models as shown in Table 4. Aand B were the significant model terms for AS-MBR and only B for CAS-MBR. It was noticed that for CAS-MBR system the response was independent of HRT. This difference was attributed due to the carbon source which was consumed in the first compartments of the CAS-MBR system, while effective nitrification has been occurred at the last ones. In other words, because of low F/M values in last compartments of CAS-MBR system, microorganisms were

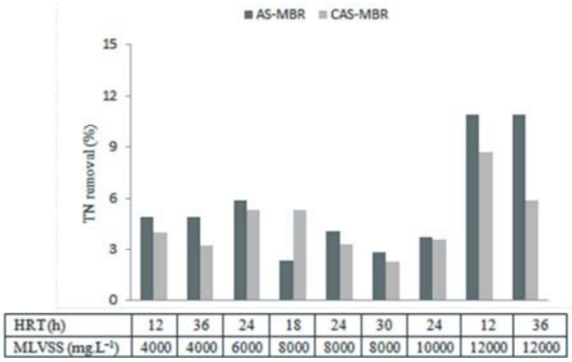

Fig. 9: TN removal under different operational conditions studied.

forced to use nitrogenous source as food. The amount of 21.1 and 22.1% were found as the maximum TKN removal for the AS-MBR and CAS-MBR, respectively.

Total Nitrogen (TN) Removal: In conventionally treatment processes, biological nitrogen removal is achieved by nitrification followed by a denitrification process, *i.e.* (a) aerobic nitrification of NH_4^+ by chemolithoautotrophic bacteria to NO_2^- or NO_3^- with O_2 as the electron acceptor and (b) anoxic denitrification of NO_2^- or NO_3^- to gaseous N_2 by heterotrophic microorganism using organic matter as carbon and energy source [29].

Fig. 9 shows the TN removal for all experiments in the AS-MBR and CAS-MBR. Maximum values of TN removal (10.94% in the AS-MBR and 8.70% in CAS-MBR) were obtained at the highest MLVSS concentration of 12000 mg.L^{-1} in the both systems. The TN removal percentage in the AS-MBR was higher comparatively to CAS-MBR and this is attributed to the endogenous respiration in the low F/M ratios in the system [27]. Moreover, 11-12% of microbial cell content was composed of nitrogen and the total nitrogen used for cell generation was greater than the amount of TN removed. This might be due to the release of nitrogen gas from cells during microbial dissimilation.

Total Phosphorous (TP) Removal: Phosphorus removal in biological treatment process can be done by repeating anaerobic and aerobic steps and this will lead to phosphorus accumulating organisms (PAOs) in the form of polyphosphate. ANOVA results in Table 4 shows that A, B, B^2 and AB were significant model terms for AS-MBR, whereas for CAS-MBR it was A, B and AB for TP removal. It was found that both systems, at the operating conditions applied, did not show good removal of TP. The maximum removal of TP achieved by AS-MBR and CAS-MBR was about 13.0 and 13.3% respectively. Low percentage of TP removal is expected due to the low influent BOD/COD ratio (0.22-0.35) and high concentration of NO_3^- (21-36 mg.L^{-1}) and PO_4^{3-}(8.6-9.8 mg.L^{-1}) ions in both systems. It is known that $NO_3^-$and PO_4^{3-} ions could interfere as an oxidative agent [30, 31]. However, there was a small increase in TP removal with increasing HRT and MLVSS concentration in the both systems. This is mainly because of increasing COD removal at high values of HRT and MLVSS concentration. Furthermore, in this condition, microorganisms use phosphorus for their cell growth [5].

Amount of TP used for cell generation was also calculated based on 1% phosphorous content of cells. Similar to nitrogen, results showed that in low MLVSS concentrations, the TP used for cell generation was greater than TP removed. Probably, it was related to partial anaerobic and/or anoxic conditions were occurred during retention in the settling chamber. In the described conditions, phosphorous was released from cell as polyhydroxybutyrate (PHB) [5]. Moreover, high level of DO and continuous aeration, could be the reason for low nutrients removal in the MBR systems [32]. Therefore, for the systems with the aim of nutrient removal, the intermittent aeration and/or lower aeration rate is strongly recommended.

Process Optimization: From the study, it was found that TCOD removal, rbCOD removal, sbCOD removal and effluent turbidity were the most critical responses to achieve a highly treated effluent. Thus, to optimize the process, TCOD and effluent turbidity wereconsidered as main parameters to provide two groups *i.e.* Group 1 with COD removal ≥ 80% and Group 2 with COD removal ≥ 90% and each group investigated at three levels of the effluent turbidity (5, 10 and 15 NTU). Fig. 10 shows graphical optimization, which display the area of feasible response values (shaded portion) in the factors space. The graphical optimization results allow visual inspection to choose the optimum operating conditions.

Fig. 10 displays the overlay plot forCOD removal ≥ 90% and Fig. 11 for COD removal ≥ 80% for both systems. For COD removal ≥ 90%, an optimum condition was not found for AS-MBR (Figs. 10a1, 10a2 and 10a3); however, for CAS-MBRan optimum region covered by HRT of 12-35 h and MLVSS more than 10000 mg.L^{-1} was found (Figs. 10b1, 10b2 and 10b3). For COD removal ≥ 80% an optimum region was found for both systems (Fig. 11). As a conclusion, the CAS-MBR showed higher treatment capacity at the same condition compared to AS-MBR.

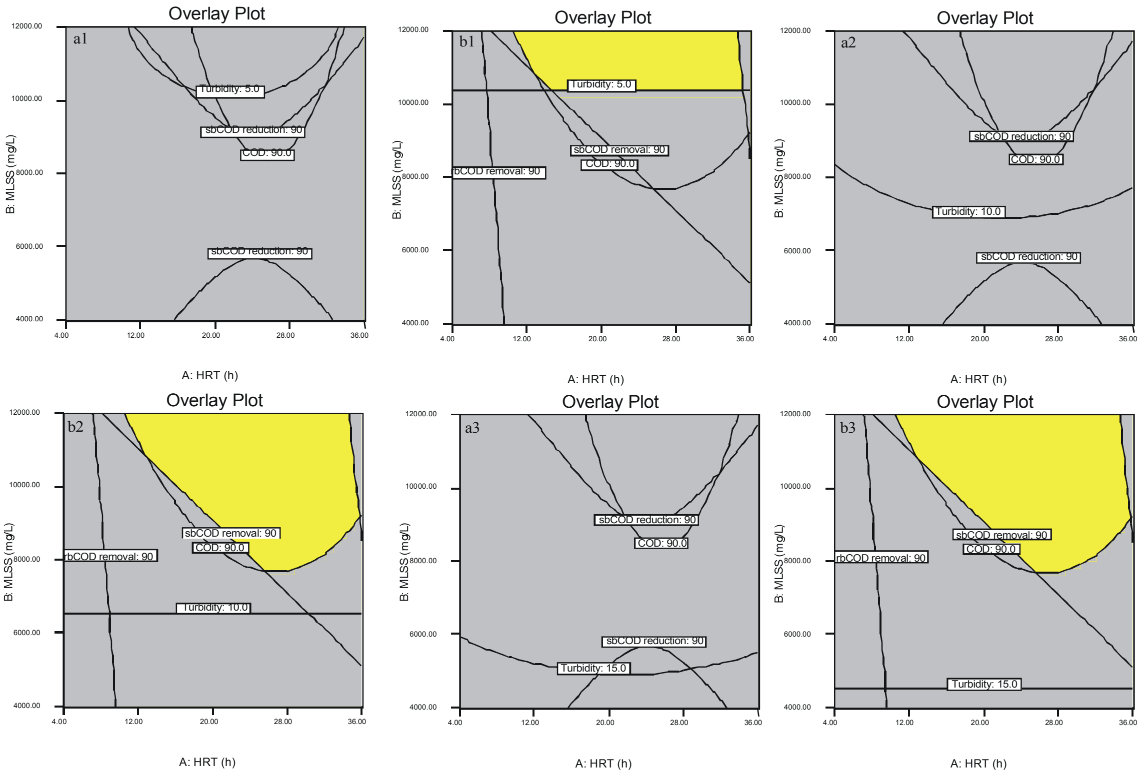

Fig. 10: Overlay plots for the optimal region with 90% COD removal at three levels of effluent turbidity (5, 10 and 15 NTU): (a) AS-MBR, (b) CAS-MBR.

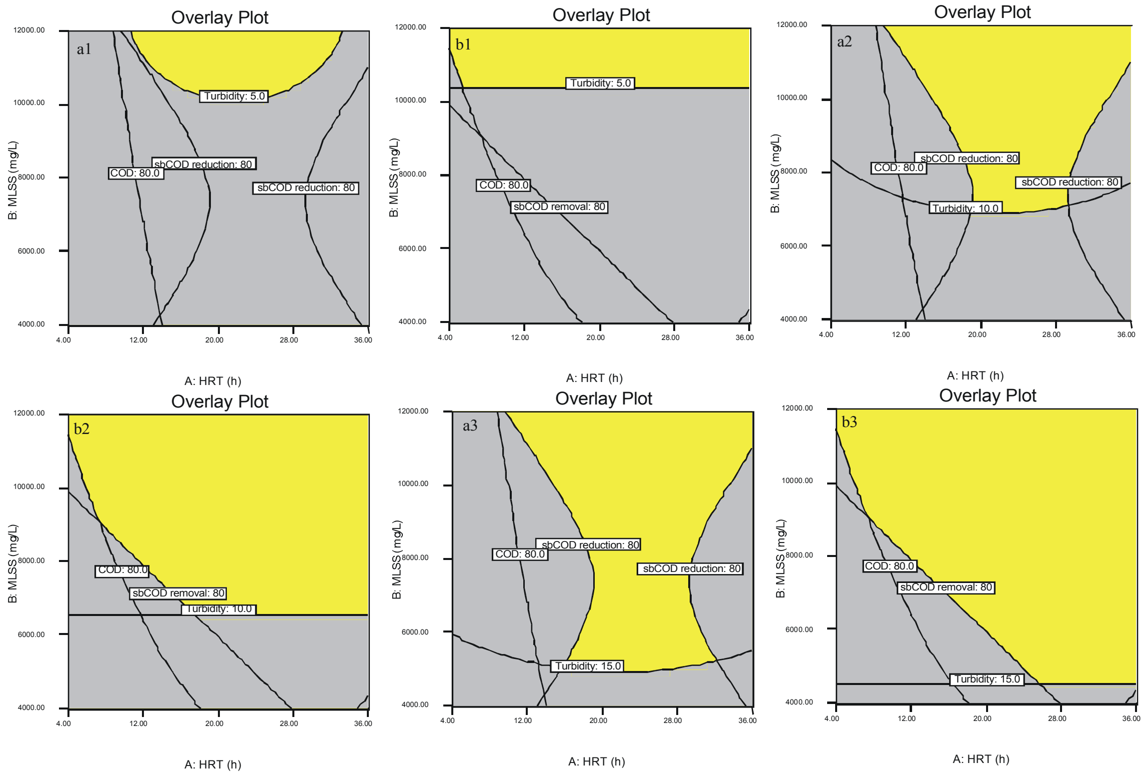

Fig. 11: Overlay plots for the optimal regionwith 80% COD removal at three levels of effluent turbidity (5, 10, 15 NTU): (a) AS-MBR, (b) CAS-MBR.

CONCLUSION

Two lab-scale membrane bioreactor with different hydraulic flow regimes (AS-MBR and CAS-MBR) were successfully designed and operated for FIW treatment. Maximum TCOD removal efficiency for AS–MBR was 94% at HRT of 24h and MLVSS of 12000 mg.L^{-1}; while for CAS-MBR it was more than 98% at the same condition. CAS-MBR was more efficient than AS-MBR in terms of sbCOD removal due to the specific regime. Microfiltration showed a significant effect in turbidity reduction; however, the need for microfiltration in CAS-MBR was less than AS-MBR. The optimum region for CAS-MBR is at HRT 12-35 h and MLVSS of more than 10000 mg/l. AS-MBR could not achieve COD removal higher than 90% with an effluent turbidity less than 15 NTU while CAS-MBR was able to achieve COD removal higher than 90% with an effluent turbidity even less than 5 NTU. As a conclusion, the CAS-MBR showed higher treatment capacity at the same condition compared to AS-MBR.An intermittent aeration and/or lower aeration rate are recommended for both systems as an effective strategy to remove nutrients.

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