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Upgrading of Al-Rustamiyah Sewage Treatment Plant Through Experimental and Theoretical Analysis of Membrane Fouling

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Abstract

Al-Rustamiyah plant is the oldest and biggest sewage treatment plant in Iraq; it locates in the south of Baghdad city. The plant suffers from serious problems associated with overflow and low capacity. The present work aims to upgrade the heart of biological treatment process through suggesting the use of membrane bioreactor; (MBR). In this work, fouling of membrane during sewage treatment has been analyzed experimentally and theoretically by fouling mechanisms. Aeration has been applied in order to control fouling through producing effective diameters of air bubbles close to the membrane walls. Effect of air flow rate on flux decline was investigated. Hermia's models were used to investigate the fouling mechanisms. The results showed that cake formation is the best fitted model ($R^2 \geq 0.98$) followed by intermediate blocking occurred with 9 L/min aeration rate. Cake layer formation is the best fit mechanism in all aeration rates (1-9 L/min) in presence of microalgae. SEM images of the membrane surface before and after filtration showed high density pores membrane surface proved a cake fouling occurring. It was found that aeration represents the most effective technique for fouling domination in addition to its important economic aspects for algae growth and propagation. An enhancement of 70.8% in flux at 9 L/min air flow has been revealed. MBR proved to be more efficient and more convenient than activated sludge since it eliminates the needing of sedimentation tanks and upgrading Al-Rustamiyah plant that has low available space for expansion.

Key words: Aeration; fouling mechanisms; membrane filtration; sewage treatment; membrane bioreactor.

Introduction

Clean water is a great uttermost, especially with diminishing of water resources all over the world. A submerged membrane bioreactor is a promising technique to produce clean water from sewage wastewater, but, membrane fouling constantly holds back the membrane performance. The submerged membrane bioreactor (SMBR) offered a very attractive solution to a numerous wastewater treatment issues, especially, in the field of biological treatment for industrial or sewage wastewater. The widespread range of applications comes from its integration between the biological treatments of activated sludge plus membrane separation process without needing of further settling tanks which diminishes the system footprint, with enclosing of high effluent quality. Rather than separation of organic pollutants that has been carried out by microfiltration (MF) or ultra filtration (UF), but the membrane fouling restricts its expanded applications. Therefore, to get advantage from this widespread usage, plentiful studies have been carried on membrane bioreactor (MBR) to examine the fouling action on membrane performance [1 and 2]. The effect of biomass fouling that is due to microorganisms which are separated by MF (≥0. 1) and UF (0.01-0.1µm) membranes. Previous researches focused on modeling of membrane fouling concentrated on characterization of fouling [1, 2, 3 and 4].

Hermia [5] suggested four various models to describe fouling, they were: complete pore blocking, standard pore blocking, intermediate pore blocking, and cake formation. Other researchers [6 and 7] have supported that, fouling has been caused by several mechanisms, the resistance in series model uses Darcy's law which split the total resistance into membrane resistance and cake formation but they were not applied for bioreactors. Hermia's model has been applied to aerobic MBRs [8]. The fractal permeation model developed by Meng [9], produces a potential evaluation to the permeability of cake layer during activated sludge microfiltration. A comparative model considered the membrane fouling by decreasing its surface area due to foulants engagement [10]. In order to keep high performance in MBR operation, the control on fouling must be done. Different techniques have been established for this purpose. The popular methods for fouling control involve: optimizing the hydrodynamic conditions in MBR, run of membrane systems below the critical flux, pre-treatment of feed, membrane backwashing and cleaning [11], or involving membrane coating [12], and adsorption of suspension [13]. Recently, the most common and high efficiency strategy is conducting of air scour to control the fouling extensively by mitigating the fouling through the effect of shear stress. The shear stress has a limited effect on prohibition of small particles (<1µm) to deposit on membrane surface, but this aeration process represents the important operation cost in MBR.

Bio-treatment of wastewater using the microalgae is predominantly charming method since it has an ability of photosynthesis transforming solar energy into advantageous biomass consolidating nutrients as nitrogen and phosphorous to eutrophication [14]. The technology and biotechnology of microalgae culture and its using in wastewater treatment have been frequently sought [15, 16, 17, 18, 19 and 20]. In wastewater such as sewage wastewater system, it has been planned to eliminate, at most dissolved nitrogen and phosphorous, is coming to be most significant stage in the treatment. The drainage of these nutrients into sensitive water bodies impresses the eutrophication by stimulating the growth unfavorable plants for example algae and aquatic macrophysics. One more impact of nitrogen compounds in wastewater are toxicity of non-ionized ammonia to fish and other aquatic organisms, conflict with disinfection where a free chlorine residual in demand and methemoglobinemia in influents as a result of interoperate nitrate concentrations (more than 45 g/m^3) in drinking water [21]. The treatment of sewage is aimed also to remove all the organic ions by means of biological or chemical methods. The biological process is more efficient and cost effective than chemical method that cause another pollutions by the chemicals used, rather than additional cost consumed for further steps of treatment. Several investigations mentioned on the biological oxidation to eliminate more than 90% of bacteria from sewage using different ways of aeration, while the suspension is kept through mechanical agitation or mixing by air diffusers [22]. Aeration gives advantages of MBR through offering oxygen mass transfer to algae growth, although control on fouling of membrane surface by changing the aeration rate and consequently shear stress exists in the vicinity of the membrane by fine air bubbles leading to fouling mitigation. Many researchers studied the effect of aeration on membrane fouling in different conditions, but for MBR, limited studies have been found on controlling of fouling by changing the aeration conditions and hydrodynamics [23, 24, 25 and 26]. In Iraq, Al-Rustamiyah plant is the major site for sewage treatment placed in the south of Baghdad city. The plant suffers from many problems associated with overload and lack in its specific design efficiency especially with overpopulation and water limitations set by neighboring countries in the recent years. According to our information, there is no existent study dealing with analysis of membrane fouling during sewage handling in SMBR, although, it is a quite serious problem facing this needful treatment. Thus, the main objective of this work is to upgrade Al-Rustamiyah sewage treatment plant through design and operate the algae submerged membrane bioreactor specialist for using to treat sewage wastewater, as well as analyzing the fouling mechanisms to award specific design and operating hydrodynamic parameters.

Mechanisms of Membrane Fouling

Hermia [5], concluded a mathematical model (Equation 1) to characterize the permeate flux decline. This model is based upon conventional fixed pressure filtration. The fouling mechanism is sympathized involving this blocking filtration law or Hermia's model.

$$(d^2t/dV^2) = k(dt/dV)^n \qquad \ldots(1)$$

The exponent n in Equation 1 identifies kind of filtration mechanisms. The fouling mechanisms characterizations are donated bellow.

1. Complete Pore Blocking

It takes place when the sizes of filtration solutes are bigger than membrane pores. The solutes will fully hinder or plug the membrane pores without overlap of the solutes. The filtration impedance rises when number of unclosed membrane pores reduces [27]. Consequently, permeate flux decreases exponentially with time. Filtration volumetric flow rate will relate with time as in Equation 2:

$$Jt = J0[\exp(-\varepsilon ct)] \qquad \ldots(2)$$

Where, $\varepsilon c = A_b V0$

A_b is the blocked surface area per unit of total permeated volume, and V_0 is the initial volumetric flow rate per unit area of porous membrane surface. So, the evaluated development with time of permeates volumetric flow are presented in Equation 3:

$$\ln Jt = \ln J0 - \varepsilon ct \qquad \ldots(3)$$

2. Standard Pore Blocking

It has been titled as internal pore blocking. It happens when tiny particles precipitate on the walls of membrane pore [28]. However, it occurs while the sizes of the solutes become lesser than the size of the pore entrances. Precipitation of particles on the walls or inside the membrane holds-up considerably raise the resistance of filtration and lighten the rate of filtration while the volumes of membrane pore are diminished.

The volumetric flow rate and time is correlated as in Equation 4:

$$Jt = J0/(1+\varepsilon st)^2 \qquad \ldots(4)$$

where $ArV0/(J0)^{1/2}$

Ar is the decrease in pores cross section area per unit of permeate flux.

A linear equation which represents volumetric flow rate with time is specified by Equation 5:

$$1/(Jt)^{1/2} = 1/(J0)^{1/2} + \varepsilon st \qquad \ldots(5)$$

3. Intermediate Pore Blocking

Here, the particles diameters are quite identical to the membrane pore size. The mechanism supposes that particles may be taken off regularly above the prior precipitated particles. Several particles can immediately prevent and coat somewhat effective membrane space [27]. According to that hypothesis, any position at the surface of membrane is posed to a similar opportunity for covering by particles. Thus, it has been known as intermediate pore blocking. The volumetric flow rate with time correlation is shown by Equation 6:

$$Jt = J0/(1+\varepsilon it) \qquad \ldots(6)$$

where, $\varepsilon i = A_b V0/J0$.

Now, the attributed growth in the permeate flux with time is offered in Equation 7:

$$1/Jt = 1/J0 + \varepsilon it \qquad \ldots(7)$$

4. Cake Formation

This mechanism may be carried out while the deposited particles showing a form of surface layer. Commonly this model denoted while the particles size sited in are bigger than the membrane pore size. It supposed that particles can be fixed on another pro-settled particles that coming early and then covering the surface. At this situation, the space on membrane surface is not available and the time for filtration has been extended [29]. Therefore, there is a higher level of particles in this type of fouling. Thus, it is well recognized as "cake formation" model. A correlation of volumetric flow rate with time is shown in Equation 8:

$$Jt = J0/(1+\varepsilon cft)^{1/2} \qquad \ldots(8)$$

Where:

$$\varepsilon cf = C/(J0)^2 \qquad \ldots(9)$$

And

$$C = (2Rr)A_b kV0 \qquad \ldots(10)$$

By conducting Equation 10 with Equation 9, Equation 11 will procure as:

$$\varepsilon cf = (2Rr)A_b kV0/[(J0)^2] \qquad \ldots(11)$$

Where $1/A_b k$ is deducted the permeate volume accumulated per unit area and Rr is the ratio of the cake layer resistance to a clean membrane resistance. The relation of permeate volumetric flow with time is offered in Eq. (12):

$$1/(Jt)^2 = 1/(J0)^2 + \varepsilon cft \qquad \ldots(12)$$

Table 1 shows the fitted equations and the values of n.

Table 1: Fouling mechanisms or blocking models

Blocking type	Fouling idea	Particular equation	n
Complete pore blocking	Pore sealing	$\ln Jt = \ln J0 - \varepsilon ct$	2
Standard blocking	Pore walls enclosed	$1/(Jt)^{1/2} = 1/(J0)^{1/2} + \varepsilon st$	3/2
Intermediate blocking	Pore sealing and membrane surface deposition	$1/Jt = 1/J0 + \varepsilon it$	1
Cake formation	Formation of Cake layers on surface	$1/(Jt)^2 = 1/(J0)^2 + \varepsilon cft$	0

Materials and Method

1. Experimental Setup

A submerged membrane bioreactor used in this work was designed, fabricated, tested, and run to treat a synthetic sewage wastewater. It has been consisted of 30×50×70 cm Plexiglas tank with five sheets of PVDF 32×22×0.6 cm flat sheet membrane supplied by Shanghai SINAP membrane technology, China, the specifications of the membrane sheet was illustrated in Table 2. The spacing between membrane sheets was fixed to be 0.7 cm. At the bottom of the tank there was a 3 inches diameter and 12 inches long, fine bubble air diffuser made from high grade EPDM, with pore size of 2 mm, see Figure 1, gives air bubble size of 1-3 mm, this air diffuser has been supplied by KAMAir, SANLEE Industry, Taiwan. The TMP was fixing to be 1-4 bar be means of air gauge (Weld Ro Model: WR 320, range 0-16 bar). The air flow rate was adjusted using air Rotameter (Dwyer CAT. NO.: RMA-21-SSV, S.S. range: 1-10 L/min. AIR). Permeate has been withdrawn from membrane sheets by 2-stage vacuum pump (type: JK-WRV-2, Japan) with volumetric flow rate of 2.5 m^3/h, and ultimate pressure of 5×10^{-2} pa, and vacuum pressure gauge (MTI corporation). Figure 1 shows the schematic diagram of experimental set-up.

Table 2 Specifications of flat sheet membrane (SINAP-10)

Parameter	Unit	Value
Pore size	µm	0.1
Effective Membrane area	m^2	0.1
Size	mm	220×320×6
Weight	Kg	0.4
Flux	L/day	40-60
Material	-	PVDF

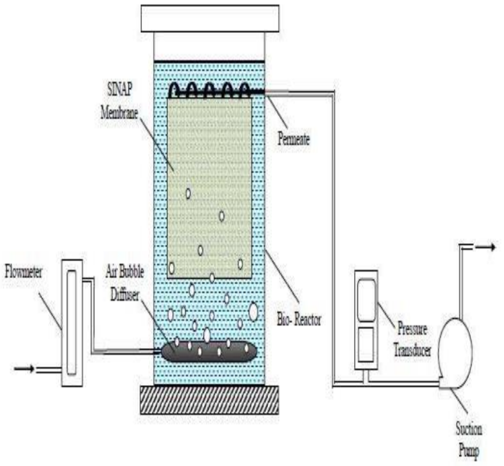

Fig. 1: Schematic diagram of the membrane bioreactor set-up used

2. Wastewater

A synthetic sewage wastewater was prepared and used to simulate the treatment of actual sewage; its compositions for 55 liters; are as follows: Peptone (0.825 gm), $NaHCO_3$ (16.683 gm), KNO_3 (1.925 gm), NH_4NO_3 (0.5775 gm), $NaH_2PO_4.2H_2O$ (0.0696 gm), meat extract (0.9166 gm).

3. Microalgae

The microalgae have been used for biological treatment of synthetic sewage wastewater. The microalgae was selected to be a strain of *Sperolina* *platensis* has been cultured in algae culture room under conditions (light intensity of 100 lux, aeration rate of 1 L/h, and a constant temperature of 21 ^{o}C) stay 10 days before using in MBR to remove nutrients from wastewater. The removal of nutrients from sewage wastewater will be considered in a future work.

4. Experimental Procedure

After the microalgae was cultivated for 10 days. 10% concentration was used in MBR mixed with prepared synthetic sewage and entered into MBR directly. The run was beginning by opening the air valve and adjusting the air flow rate (3, 6 and 9 l/min). Air bubbles were released from the diffuser as small and fine bubbles have been distributed uniformly between membrane sheets. Permeate has been withdrawn from each membrane sheet using a vacuum pump and collected in a graduated cylinder to measure the permeate flux at constant TMP. The effect of air flow rate on permeate flux was noticed and recorded reflecting the presence of membrane fouling. Also the increase in TMP certified membrane fouling. The run continued for a time interval 0-30 min for each air flow rate value and permeate has been recorded.

Results and Discussion

1. Aeration Impact

For synthetic sewage wastewater used in this study, is a type of biological solutions contain biodegradable chemicals and also algae suspension. This represents the major fouling source presents is this work where the microfiltration of pore diameter is ≥0. 1 has been used.

In this work, Hernias models were involved to explain fouling mechanisms which take place through microfiltration and biological treatment of synthetic sewage.

The aeration influences have been clearly observed in this work through monitoring the air bubbles filling the spacing between membrane sheets; these air bubbles represent the provenience of the pivotal shear stresses. Figure 2 shows the air bubbles distributed between membrane sheets spacing for the two systems used in the study at a same aeration rate (Qg=6L/min). It can be seen that smaller bubbles found in algae plus wastewater system (Figure 2, b) because of microalgae presence goes to air bubbles break up.

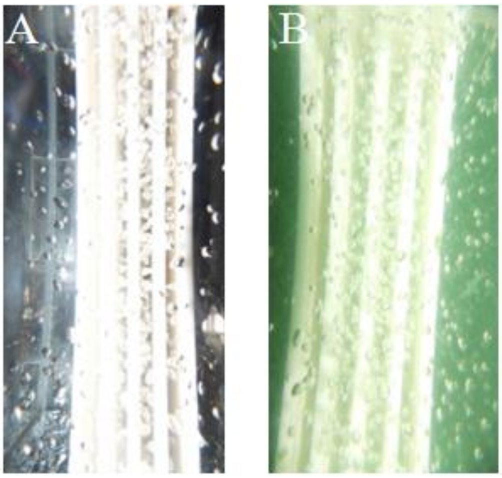

Fig. 2: Photos of air bubbles filling the spaces between membrane sheets (a) for wastewater system, (b) for wastewater and algae suspension

To investigate the effect of the air flow rate upon the membrane fouling, three levels of air flow rates (3, 6 and 9 L/min) were employed. Figure 3a, shows the declines in permeates flux versus time for different aerations. It has been shown that, two phases of flux reduction have been observed, the first phase represents the flux decline through initial 25 minutes of filtration. In this phase, the decline is significantly higher in all aeration rates, however, it is further sharp at a low air flow rate (Qg=3 L/min), and less sever at a higher rate (6 L/min). This phase of flux decline refers to complete pore blocking, making that minimal fluid that is passed through the pores of the membrane. The second phase of flux decline exists in the time range from (time=25 min and above), the decline is significantly observed in the low air flow rate (Qg= 3 and 6 L/min). This second phase of decline is due to the cake layer of the solid particles accumulated on the surface of the membrane. Whilst, for high aeration rate (Qg=9 L/min), the reduction in flux tends to show a sacrificial one phase flux decline, this has been attributed to the cake layer formation on the membrane surface. Several investigators detected comparable effects [30, 31, and 32]. Furthermore, we can observe clearly, that at high aeration rate (Qg=9 L/min), the amount of flux is at elevated levels than those at lower aerations (Qg=3, and 6 L/min). This can be attributed to the depressed in resistance to filtration because of high shear stress values near the membrane walls resulting from high intensity of air bubbles at a high air flow rate. This high shear stress encourages the mitigation of fouling on the membrane surface leading to easier pass of liquid through the semi permeable membrane.

The normalized flux decline curves for algae wastewater system (algae in the concentration of 10% added to the synthetic sewage wastewater) are shown in Figure 3b. In this case, the wastewater solution becomes denser with suspended microalgae, and biomass produced from its growth. Thus, it is expected that lower values of permeate flux have been obtained. We can recognize two phases of flux decline at all aeration rates. The first phase represents the initial period of filtration (until time=35 min), whereas in the first phase, a sharp decrease in flux occurred in all air flow rates, this is due to complete membrane pores blocking with large solid particles. After the first 35 minutes, the second phase enters indicated a slight reduction in flux with time because of cake formation. Also, the values of flux at high aeration (Qg=9 L/min), are much elevated than in lower aeration rates (Qg=3, and 6 L/min), this has been attributed to the concentration polarization and high shear stresses produced by high intensity air bubbles at higher aeration. The results of Kocadagistana and Topcub [33] confirm our findings.

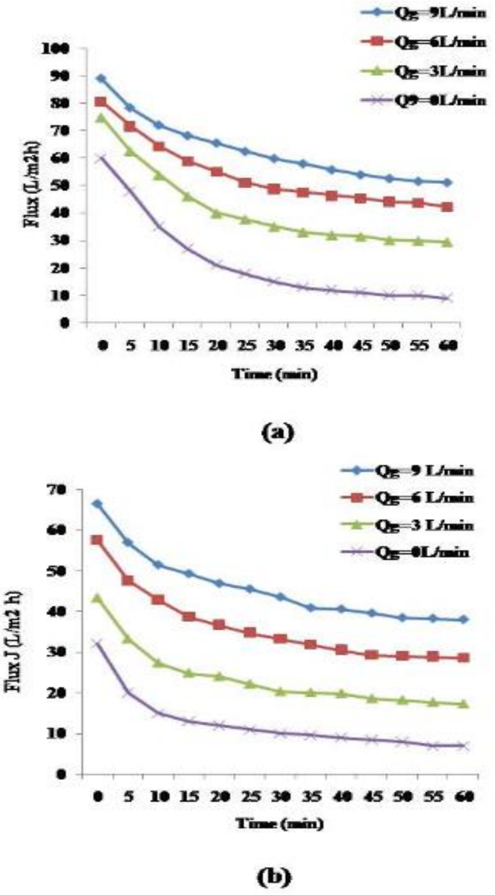

Fig. 3: Normalized flux declines in various aeration rates for (a) synthetic wastewater, (b) algae suspension

2. Fouling Mechanisms Analysis

Figure 4 (a-d), clarifies the fitting of the achieved experimental data with the wastewater system and aeration rates (3, 6 and 9 L/min) to the various attributed fouling mechanisms. From the figure, we can recognize obviously that the membrane suffers from a cake layer fouling since the mechanism is fitted well with the experimental results in the all aeration rates , while, the intermediate blocking is less fitted.

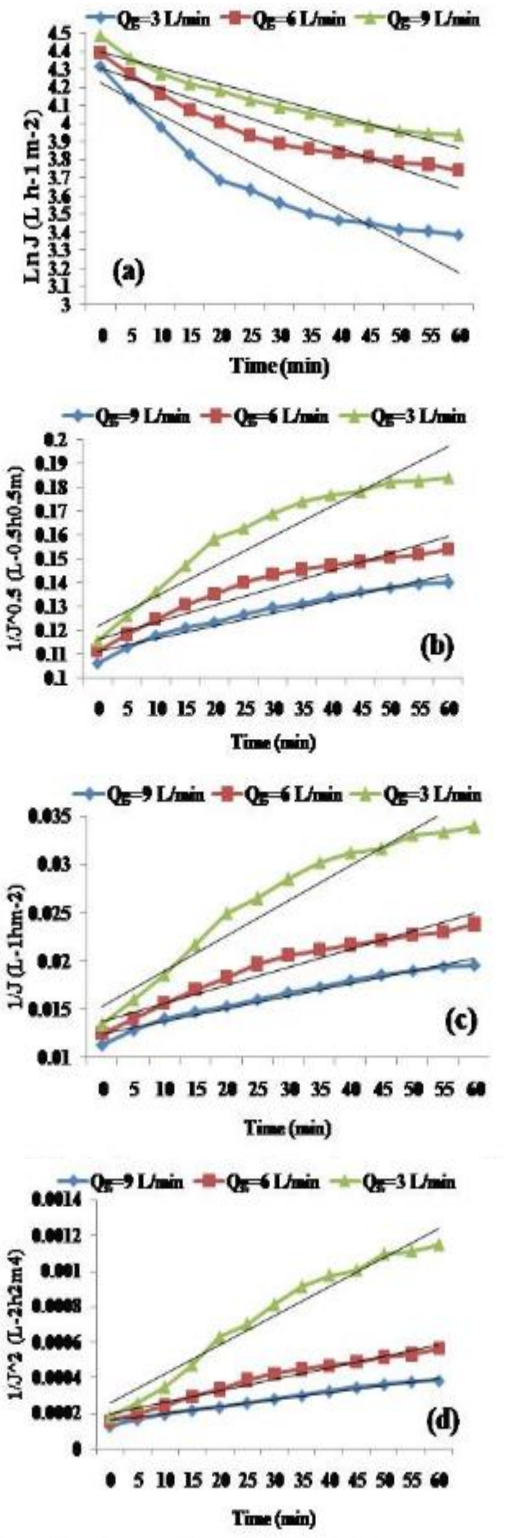

Fig .4: Effect of various aeration rates on permeat fluxes (wastewater), according to the predicated fouling mechanisms: (a) complete pore blocking, (b) standard pore blocking, (c) intermediate pore blocking, (d) cake formation

The most fitted cake formation is found at 9L/min, this can be attributed to the large particle size of the fouling compounds present in the synthetic sewage used. This particles deposit on the surface of submerged membrane forming cake layer, rather than smaller particles may enter to the pores could produce an intermediate pore blocking mostly on 9L/min aeration rate. This result shows some deviation from the fact that fouling has been reduced with increasing the air flow rate. Our explanation is that at a high air flow rate, gas hold up will increase that means the amount of air inside the liquid become higher, because of elevated turbulence leads to air bubbles break up produced smaller bubbles. These small bubbles have lower shear stress than a larger one. Table 3, shows the fitted R^2 values. Also, Table 4, explains the fit of the permeate fluxes to the predicated fouling mechanisms so as to attend with the impact of the different aeration rates on fouling.

Table 3: Values of R^2 obtained from experimental data of membrane fouling with wastewater system

Mechanism	Qg =3 L/min	Qg =6 L/min	Qg =9 L/min
Complete pore blocking (n=2)	0.825	0.884	0.934
Standard pore blocking (n=3/2)	0.884	0.915	0.954
Intermediate pore blocking (n=1)	0.925	0.939	0.968
Cake formation (n=0)	0.969	0.969	0.980

Table 4: Fitted Hermias model parameters and effect of aeration upon membrane fouling using wastewater

Qg (L/min)	εc (s^{-1})	εs ($s^{-1/2}$ $m^{-1/2}$)	εi (m^{-1})	εcf (sm^{-2})
3	0.087	0.006	0.001	8×10^{-5}
6	0.055	0.003	1×10^{-5}	3×10^{-5}
9	0.044	0.002	1×10^{-5}	2×10^{-5}

It can be shown from the deviations of the experimental results and the predicated models that the cake formation is the more significant mechanism appeared in the wastewater treatment since it produced a greatest R^2 values (0.969, 0.696, and 0.980) for all aeration rates applied. While, the other mechanisms are also somewhere applied, but with less correlate. Figure 5 (a-d), displays the fouling mechanisms achieved with algae wastewater (algae added to the wastewater solution). It can be distinguished that, cake formation mechanism only applied to all aeration rates, although it is more significant in low aeration (3 L/min). This can be attributed to the low turbulence level leading to solid matters deposition on the membrane surface forming a cake layer. Whilst, for higher aerations (Qg=6, and 9 L/min), the fouling mechanisms have been revealed, the cake formation presents in low correlation fitting. The reason can be assigned to high turbulence encourage the solid particles to move away from the surface of the membrane, rather than the effective influence of air bubbles shear stress on the membrane surface assist in fouling mitigation. Thus, the cake formation mechanism has been applied to all aeration rates fouling results. Also the high particle size of the algae wastewater solution hinders it to enter through the small pore size of the MF (=0.1 µm). These results are supported by Gao [30].

Tables 5 and 6 show the fitted R^2 values and explains the fitting of permeate fluxes to the predicated fouling mechanisms so as to attend with the impact of different aeration rates on membrane fouling. It confirms the existence of the high values of R^2 (0.973, 0.964, and 0.958) for cake formation mechanism in all aeration rates with more severe fouling at low aeration.

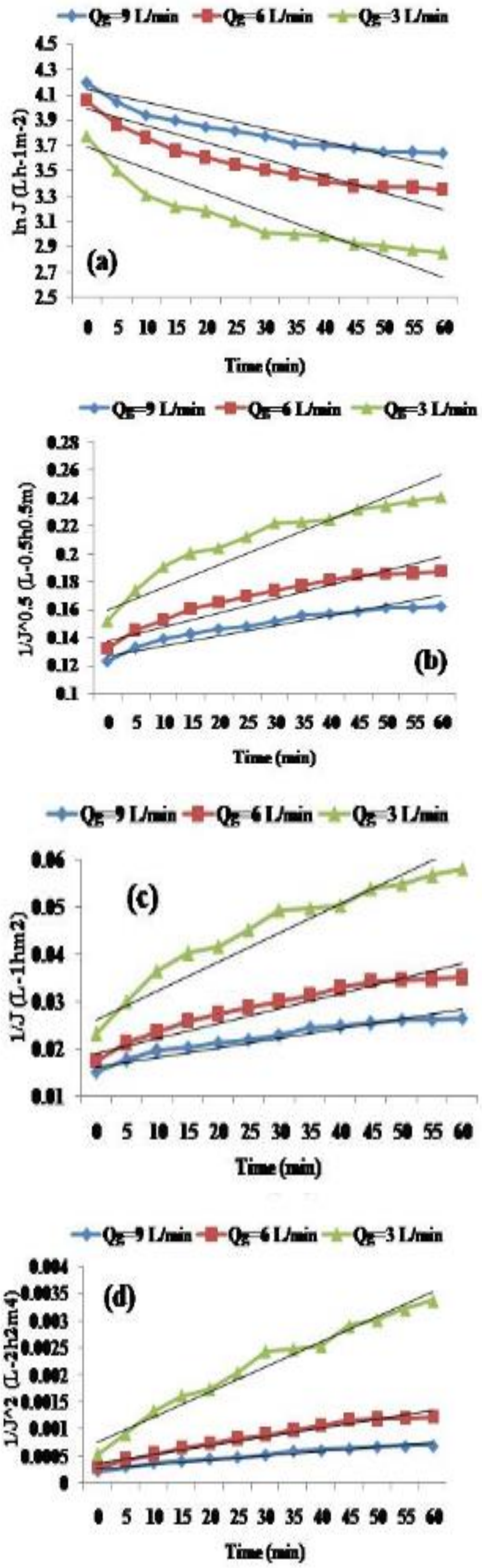

Fig. 5: Effect of various aeration rates on permeate fluxes (for algae wastewater system), according to the predicated fouling mechanisms: (a) complete pore blocking, (b) standard pore blocking, (c) intermediate pore blocking, (d) cake formation

Table 5: Values of R^2 obtained from experimental data of membrane fouling with algae and wastewater

Mechanism	Qg =3 L/min	Qg =6 L/min	Qg =9 L/min
Complete pore blocking (n=2)	0.723	0.804	0.816
Standard pore blocking (n=3/2)	0.821	0.864	0.866
Intermediate pore blocking (n=1)	0.895	0.910	0.905
Cake formation (n=0)	0.973	0.964	0.958

Table 6: Fitted Hermias model parameters and effect of aeration on membrane fouling with algae wastewater

Qg (L/min)	εc (s^{-1})	εs ($s^{-1/2}m^{-1/2}$)	εi (m^{-1})	εcf (sm^{-2})
3	0.086	0.008	0.003	1×10^{-5}
6	0.066	0.005	0.001	8×10^{-5}
9	0.052	0.003	0.001	4×10^{-5}

3. Scanning Electron Microscopy (SEM) Results

To achieve surface images of the membrane sheet before and after filtration, a scanning electron microscope (Model VEGA3 TESCAN, USA) was utilized. Figure 6a represents the image before application, it shows that the membrane had a high pore density; however, the pores were randomly distributed. Figure 6b represents the image of membrane surface after application, from this image we can see that cake formation form of fouling was clearly observed.

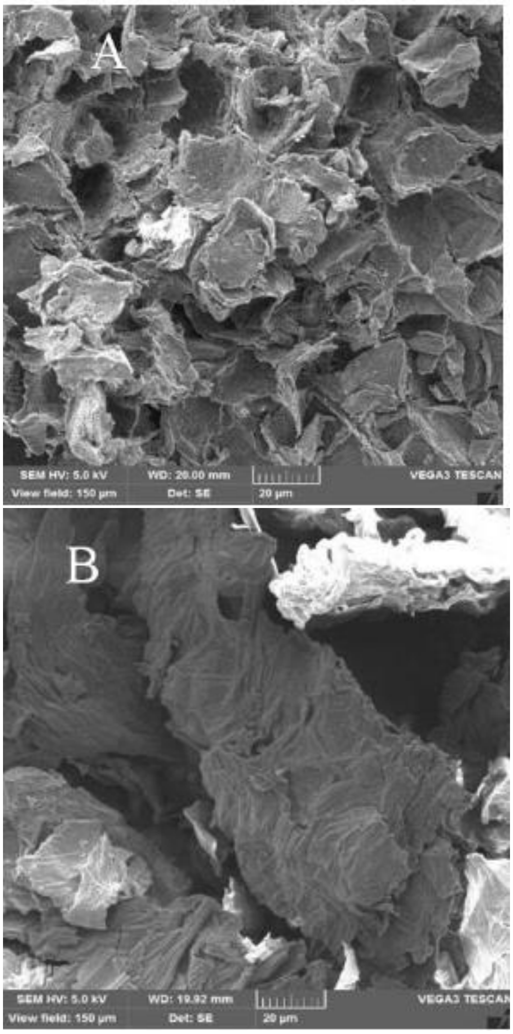

Fig. 6: SEM images of membrane surface (a) before filtration, and (b) after filtration

4. Performance Enhancement

The performance of SMBR used in biological treatment of sewage wastewater is represented by permeate flux improvement. From the analysis of fouling mechanisms mentioned in this study, we can prove a most common cake layer formation on the membrane surface. This deposition of algae particles results in a severe reduction in filtration process efficiency represented by depressed permeates fluxes. To overcome this problem, aeration has been used successfully in this study it appears as a perfect solution to this issue awarded a marked enhancement in flux during the biological treatment of sewage with microalgae. The use of the aeration method to control fouling is considered as a most power consumption stage, but in this study, it offers two advantages: the first is the microalgae growth demand, while the second profit is the control of severe cake layer formation because of microalgae existence. The values of permeate flux enhancement have been determined using Equation 13. The permeate flux increases clearly to increase aeration flow rates leading to enhancement in the filtration process efficiency by up to 72.80% at 9 L/min air flow rate.

$$\%Enhancement = J_A - J_W / J_A \quad \ldots(13)$$

Where: J_A, and J_W are permeate flux with aeration and without aeration respectively.

Conclusions

From the results, we can conclude:

- MBR is the most efficient technique for Al-Rustamiyah plant upgrading.
- The curves of permeate flux decline of the experimental data were matched to the Hermia's models.
- The best fittings were obtained in filtration of synthetic sewage. It can be recognized that, the cake layer formation is the best fitted mechanism followed by intermediate pore blocking.
- When the microalgae presents, there are much suspended solids, in this case the best fit was the cake formation mechanism.
- Aeration demonstrates an effective tool to dominate the fouling as well as algae growth requirements in MBR.
- Experimental results proved an enhancement in the permeat flux by 72.8% using 9 L/min of aeration.

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Nomenclature

J_A	Aerated permeate flux (m^3/m^2h)
Jt	Volumetric flow rate (m^3/m^2h)
J_W	Permeate flux without aeration (m^3/m^2h)
J0	Initial volumetric flow rate (m^3/m^2h)
Rc	Cake layer resistance (m^{-1})
Rf	Fresh membrane resistance (m^{-1})
Rr	Rr=Rc/Rf, ratio of cake resistance to the resistance of fresh membrane (-)
R^2	Coefficient of determination
t	Time (s)
V_0	Initial mean velocity of the filtrate (m/s)

Greek Letters

εc	Complete pore blocking model constant (s^{-1})
εs	Standard pore blocking model constant ($s^{-1/2}m^{-1/2}$)
εi	Intermediate pore blocking model Constant (m^{-1})
εcf	Cake formation model Constant ($s\ m^{-2}$)

Abbreviations

PVDF	Polyvinylidene difluoride
SMBR	Submerged membrane bioreactor

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