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The effects of SRT, OLR and feed temperature on the performance of membrane bioreactor treating high strength municipal wastewater

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ABSTRACT

The effects, of sludge retention time (SRT), feed temperature (T_f) and organic loading rate (OLR) on submerged membrane bioreactor (SMBR) performance were studied using hollow fibers (nominal pore size 0.4 μm) immersed in an aeration tank. A synthetic wastewater representative of high strength municipal wastewater was used in the study. Ten experimental runs were carried out using full factorial design with three factors and three levels (low, medium and high). These levels were 25, 30 and 35 days for SRT, 20, 30 and 40°C for T_f and 1.73, 4.03 and 6.82 kg COD/m^3 d for OLR. Variation of OLR, SRT and T_f affected the biomass development significantly. The higher OLR trials resulted in higher MLVSS/MLSS ratio and also higher increasing rate of MLSS (d(MLSS)/(dt)). For the low level OLR trials MLVSS/MLSS ratio varied between 75.3 and 82.3% and d(MLSS)/(dt) from 87.5 to 297.3 mg/l.d, whereas, for the high OLR trials they varied between 80.4 and 83.7% and 1355.4–2120.1 mg/l.d respectively. For the higher OLR, a higher aeration rate was applied to fulfill the DO demand. Therefore, for the low level OLR trials, the aeration rate and the DO were varied from 6 to 12 m^3/m^2 membrane area per hour and from 3.7 to 5.7 mg/l, respectively, whilst for the high OLR trials they varied from 6 to 18 m^3/m^2 membrane area/h and from 0.9 to 4.4 mg/l respectively. The permeate COD and NH_3-N under different operating conditions varied from 0 to 32 mg/l, and from 0.004 to 0.856 mg/l, respectively. The interaction effects of SRT and T_f on COD removal efficiency was found to be insignificant. Increasing OLR did not affect COD removal. The optimum removal efficiency of ammonia nitrogen for the low and high strength wastewater was obtained at operating conditions of high SRT and low T_f. The pH increased significantly in the aeration tank and the increase was well correlated with the feed pH (r^2 = 0.8336 for low OLR and 0.9106 for high OLR).

Keywords: Membrane bioreactor; Synthetic wastewater; Organic loading rate; MLSS development; COD removal

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1. Introduction

Municipal wastewater is essentially the mixture of domestic wastewater (main component), small amount of industrial and agro-zootechnical wastewater, storm water, drain water, surface infiltration water, and underground water. In most situations, municipal wastewater and domestic wastewater are qualitatively similar. In some cases, the discrimination between wastewater originating from municipal and domestic sources is difficult [1].

Some of the sewage treatment plants in Malaysia are located around the industrial areas. The characteristics of the wastewater discharges in these plants fluctuate due to the discharge of mixed composition of industrial wastewater and domestic wastewater resulting in high strength wastewaters. Conventional mechanized processes are incapable of producing the desirable effluent quality of the increasingly stringent discharge requirements. MBR can be introduced as an alternative technology to be adopted for treating such type of wastewater. Membrane bioreactor (MBR) has many advantages over the conventional wastewater treatment. These include producing an excellent effluent quality, meeting stringent discharge requirements, retaining all suspended particles and most soluble compounds within the bioreactor [2], significant reduction of plant footprint, good disinfection capacity, generating higher volumetric loading with less sludge production and operating at very high sludge ages without having the problem of settling. Consequently, higher strength wastewater can be treated and lower biomass yields are realized [3]. As a result, the MBR process has now become an attractive option for treatment and reuse of industrial and municipal wastewaters [4]

MBR systems can be classified in to two major groups according to their configuration. The first group is known as integrated MBR (submerged) and it involves outer skin membranes that are internal to the bioreactor [5–7]. The second configuration is the recirculated (external) MBR. In this system, the mixed liquor is recirculated through a membrane module that is outside of the bioreactor. Both inner-skin and outer-skin membranes can be used in this application. Submerged MBRs have been used worldwide with the emergence of less expensive and more resilient polymeric membranes along with lower pressure requirements and higher permeate fluxes [8].

Several types and configurations of membranes have been used for membrane applications [9]. These include tubular, plate and frame, rotary disk, hollow fiber, organic (polyethylene, polyethersulfone, polysulfone and polyolefin), metallic and inorganic (ceramic), microfiltration and ultra-filtration membranes.

Le-Clech et al. [4] had reviewed many research studies on the effect of the operating parameters on the performance of the MBR. These include aeration rate, crossflow velocity, SRT, food to microorganisms ratio (F/M), hydraulic retention time (HRT) and organic load. However, all these studies emphasized the membrane fouling. The aim of this paper is to investigate the interaction effects of the operating parameters — SRT, T_f and OLR —on the MBR performance in terms of biomass development, concentration of dissolved oxygen and the permeate quality.

2. Materials and methods

2.1. Preparation of synthetic wastewater

The composition of synthetic wastewater prepared by Jin et al. [10] was used as a guideline for the preparation of the feed wastewater used in the current study. However, in this study, the stock solution prepared was five times more concentrated than that of Jin et al. [10] (Table 1). The stock solution was kept in the refrigerator at 4°C, ready-made for daily use. The stock solution was diluted with distilled water to the desired COD concentration. In this synthetic wastewater, glucose and glutamic acid were used as carbon sources, CH_3COONH_4 and NH_4CL were used as nitrogen sources, and KH_2PO_4 and K_2HPO_4 were used to provide orthophosphate phosphorus (PO_4^{3-}-P) in the synthetic wastewater. Sodium bicarbonate ($NaHCO_3$) was used for alkalinity to keep pH at around natural [11]. Laguna clay suspension was added at a rate of 165 ml per 1 l of the synthetic wastewater to increase the suspended solids. Laguna clay suspension was prepared as described in Mohamed et al. [12].

2.2. Experimental set-up

The layout of the experimental set-up is presented in Fig. 1. The SMBR consists of two compartments: aerated and non-aerated with working volume of 20.4 L (15.3 L for aerated compartment and 5.1 L for non-aerated compartment). A microfiltration membrane module was immersed in the aerated compartment for filtration. An air pump was used to aerate the reactor through a dif-

Table 1
Composition of synthetic wastewater (mg/l)

Composition	Concentration (mg/l) [10]	Concentration (mg/l) used in the study
Glucose	670–1080	5400
Glutamic acid	285–460	2300
CH_3COONH_4	220– 50	660
$NaHCO_3$	750–3000	5000
NH_4CL	33–53	165
$KH_2 PO_4$	60	300
K_2HPO_4	80	400
$MgSO_4 .7H_2O$	33	165
$FeCl_3.6H_2O$	2	10
$CaCl_2.2HO$	20	100
NaCl	25	125

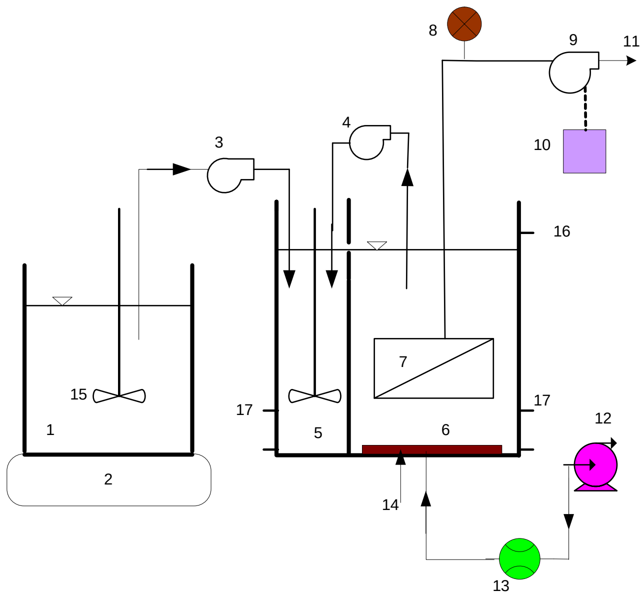

Fig. 1. The schematic diagram of MBR. 1 Feeding tank, 2 Water bath/Low temperature bath circulator, 3 Feeding pump, 4 Circulating pump, 5 Non-aerated compartment, 6 Aerated compartment, 7 Membrane module, 8 Pressure gauge, 9 Suction pump, 10 Programming time controller, 11 Final effluent, 12 Oxygen supply aerator, 13 Air flow meter, 14 Air diffuser, 15 Mixer, 16 Level controller, 17 Sampling port.

Table 2
Specification of the membrane module

Membrane material	Polyethylene
Outer diameter, µm	540
Inner diameter, µm	350
Pore size, µm	0.4
Surface area, m^2	0.2
Manufacturer	Mitsubishi Rayon (Japan)

fuser fixed at the bottom of the reactor. Table 2 shows the specifications of the microfiltration membrane used in the study.

2.3. Experimental procedure

The sludge was supplied from Tesco Damansara domestic wastewater treatment plant, Selangor state, Malaysia. The sludge was added into the reactor and the synthetic wastewater was fed into the reactor for acclimatization over 20 days. The COD in the aeration tank was analyzed to monitor the biological degradation efficiency. When the COD removal efficiency had stabled at around 80%, the system performance was considered stable and the experiment was started. Similarly, every time before starting a new experiment with higher strength wastewater, the system was allowed to acclimatize with the new condition for about 7 days.

The system was operated at different SRT, T_f and OLR for three different levels of SRT, T_f and OLR. These levels were 25, 30 and 35 days for SRT, 20, 30 and 40°C for T_f and 1.73, 4.03 6.82 kg COD/m^3.d for OLR. Water bath and low temperature bath circulator were used to control the feed temperature to the required level. The initial flux was fixed at 11.1 l/m^2.h and the corresponding hydraulic retention time (HRT) was 8.1 h. However, these flux and HRT reached up to 4.9 l/m^2.h and 19 h respectively due to membrane fouling. The feed water was pumped to the SMBR through a peristaltic pump. Wastewater was circulated from the aeration compartment to the anoxic compartment through the circulated pump at the same rate of the inflow to achieve the denitrification process. The permeate was obtained through suction with the peristaltic pump (Fig. 1) in an intermittent mode of operation. A filtration period of 8 min was followed by a filtration pause of 2 min. The most stable membrane performance could be achieved through this mode of operation [13]. A portion of sludge was removed from the reactor daily according to the operating SRT. The mixed liquor suspended solids (MLSS) and dissolved oxygen (DO) concentration were measured regularly and when the DO dropped lower than 1 mg/*l*, the aeration rate was increased. Flux and suction pressure were measured hourly during each run.

2.4. Analytical methods

The COD, NH_3-N, MLSS and MLVSS were analyzed as described in APHA [14]. Dissolved oxygen was measured by using the DO meter (Radiometer analytical, model IONcheck 20). A pH meter (Mettler Toledo, model Delta 320) was used for measuring the pH.

3. Results and discussion

3.1. Biomass development

To study the effect of OLR as well as the interaction effects of SRT and T_f on the different parameters, the experiments were categorized according to their wastewater strength level — low, medium and high as shown in Table 3.

Figs. 2a, b and c show the plots of MLSS, MLVSS and MLVSS/MLSS against time for the low, medium and high strength wastewater trials accordingly as categorized in Table 3. MLVSS in the reactor is used to describe the biomass concentration although in reality it consists of active biomass, cell debris and non-biodegradable VSS [15]. The average MLVSS/MLSS for trials 1, 4, 6 and 9 were 76.6, 82.3, 75.3 and 78.8% respectively (Table 4). Generally it was observed that for trials 1, 4, and 9, the concentration of MLSS increased slowly during the sustainable flux and then decreased gradually due to membrane foul-

Table 3
Category of the experiments based on synthetic wastewater strength level

Parameter	Low level (Trials no. 1, 4, 6, 9)			Medium level (Trials no. 2 and 10)			High level (Trials no. 3, 5, 7, 8)		
	Mim	Max	AV.	Mim	Max	AV.	Mim	Max	AV.
COD, mg/l	520	760	619	1320	1680	1500	2280	2760	2437
BOD, mg/l	360	604	473	832	1117	965	1538	2140	1871
NH_3-N, mg/l	10.9	32.6	19.4	33.0	45.0	41.5	46.6	83.3	55.4
TSS, mg/l	53	190	130	170	236	198	175	380	295
VLR, kg COD/m^3 d	1.2	1.95	1.73	3.06	4.50	4.03	5.2	7.4	6.82

AV: Average

Table 4
MLVSS/MLSS for low and high level strength trials

Trials under the same conditions		Operating conditions		MLVSS/MLSS (%)		d (MLSS)/(dt) (mg/l.d)	
Low level	High level	T (°C)	SRT (d)	Low level	High level	Low level	High level
Trial 1	Trial 3	High	Low	76.6	81.8	87.5	1355.4
Trial 4	Trial 5	Low	High	82.3	83.7	297.3	2120.1
Trial 6	Trial 7	Low	Low	75.3	80.4	–320.8	1669.3
Trial 9	Trial 8	High	High	78.8	83.1	205.7	1832.7

ing. However, MLSS concentration for trial 6 decreased slowly during the sustainable flux and the rate of decrease became faster during membrane fouling. The rates of change of MLSS concentration with time (d(MLSS)/(dt)) during the sustainable flux for trials 1, 4, 6, and 9 were respectively 87.5, 297.3, –320.8 and 205.7 mg/l. The decrease of MLSS concentration during membrane fouling is referred to as reduction of the inflow rate, which had led to reduction of the loading rate. Therefore, the rate of sludge produced was less than the rate of sludge wasted resulting in less MLSS concentration. In trial 6, the slow decrease of MLSS concentration during the sustainable flux could be related to two factors. These are:

1. The trial was carried out under low SRT meaning that the rate of wasted sludge was higher.
2. The percentage of MLVSS was low compared with the other trials (Table 4), meaning that the rate of biomass growth was lower than in the other trials.

Table 4 shows that trial 4 had recorded the highest MLVSS/MLSS value, followed by trails 9, 1 and 6 accordingly. This indicates that the operating conditions of high SRT – low T_f gave the best biomass growth, followed accordingly by high SRT – high T_f, low SRT – high T_f and low SRT – low T_f. Similar results were also obtained for the rate of MLSS increase. The results indicate also that both operating parameters have a significant effect on the MLSS concentration. However, it seemed that the effect of SRT was more significant than that of T_f, since the higher the SRT was, the higher was the percentage of MLVSS obtained. This result is in agreement with Khor et al. [16], who studied the biomass growth for MBR with different SRT conditions (5 days, 10 days and prolonged SRT) and demonstrated that the biomass build up increased with higher SRT.

The optimum temperature for nitrifying bacteria growth as found in most studies could range from 28 to 36°C although a temperature of 42°C was regarded as optimum [17]. Accordingly, high temperature for instance 40°C should produce better biomass growth. However the results of this study showed that the trend of the T_f was unclear. This could be attributed to the change of T_f which took place inside the aeration tank, reducing the temperature difference. Thus the effect of T_f was attenuated, or it could be due to the dominant effect of the SRT.

The results of MLSS and MLVSS for the medium strength wastewater trials are shown in Fig. 2b. These results are represented by trials 2 and 10, conducted under the same operating conditions. The MLVSS/MLSS for trials 2 and 10 were 78.6% and 78.9% respectively while the d(MLSS)/(dt) for trials 2 and 10 were 311 mg/l d and 850 mg/l d respectively. The higher increasing rate of MLSS for trial 10 could be related to the higher TSS contents. The average TSS values for trials 2 and 10 were 184 mg/l and 216 mg/l respectively.

Fig. 2c shows the results of the MLSS and MLVSS

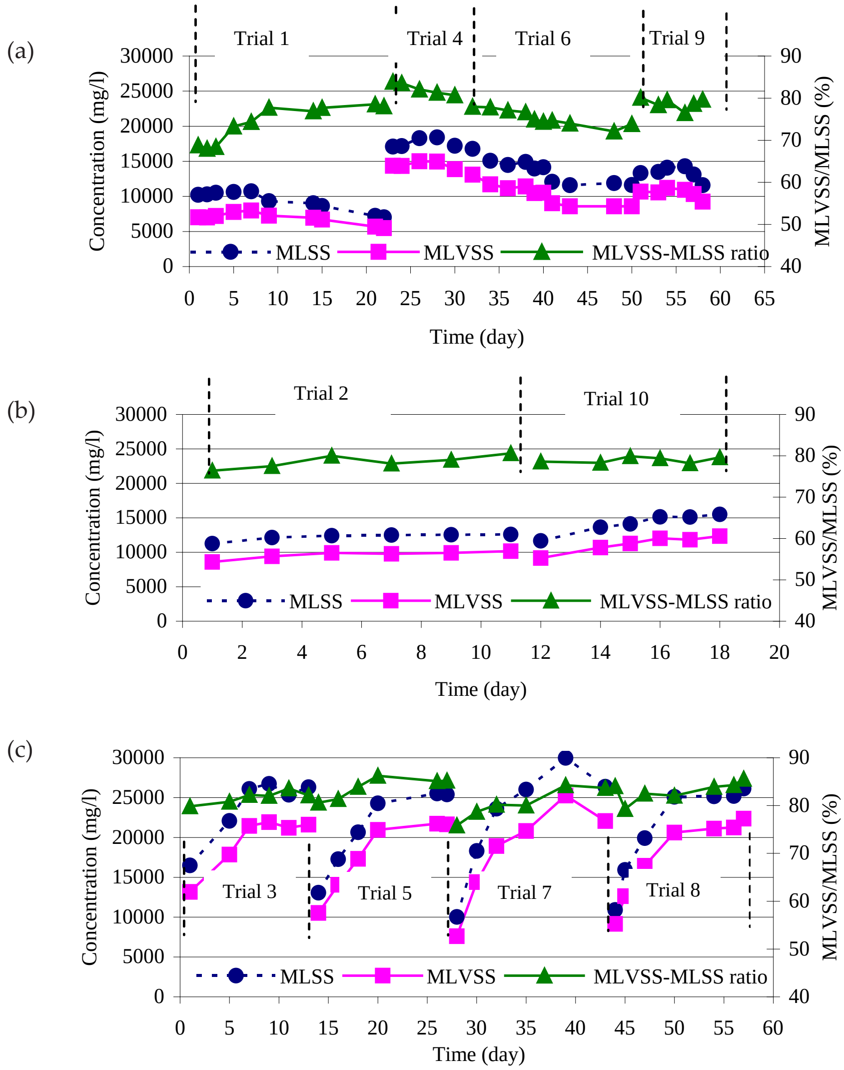

Fig. 2. Variation of MLSS and MLVSS with time for (a) low strength, (b) medium strength (c) high strength trials.

for the high strength wastewater trials. The d(MLSS)/(d*t*) for trials 3, 5, 7 and 8 were 1355.4, 2120.1, 1669.3 and 1832.7 mg/l.d respectively. In contrast, the average MLVSS/MLSS values for the same trials were 81.8, 83.7, 80.4 and 83.1 respectively (Table 4). The results showed that trial 5 had recorded the highest MLVSS/MLSS value, followed by trials 8, 7 and 3. Similar sequence was also observed for d(MLSS)/(d*t*) development. In terms of operating conditions, the variations of MLVSS/MLSS and d(MLSS)/(d*t*) followed similar trends in both low strength and high strength trials as presented in Table 4. The higher rate of d(MLSS)/(d*t*) achieved at high SRTs might be due to the lower rate of the sludge waste compared with the low SRTs. The higher MLVSS/MLSS values demonstrated that the best biomass development was achieved at the corresponding operating conditions shown in Table 4.

Comparing Fig. 2a and 2c, which show the results of four trails conducted under the same SRT and T_f but different organic loading rates (average OLR for low strength was 1.73, and for high strength it was 6.82 kg COD/ m^3.d), it is apparent that the trend of the curves for each pair of trials was different. The MLSS concentration, as can be seen in Fig. 2a, increased at a low rate during the sustainable flux and then decreased gradually during membrane fouling. However Fig. 2c shows that the MLSS concentration increased rapidly during sustainable flux and then continued increasing but with a lower rate during membrane fouling.

Table 4 shows that the high organic loading rate gave higher MLVSS/MLSS and d(MLSS)/(d*t*) values than the low organic loading rate. The results are in agreement with Holler and Trösch [18], who reported that large organic loads of wastewater resulted in high biomass production. Increasing MLVSS/MLSS with higher OLR is related to the higher F/M ratio obtained in the reactor due to higher OLR, therefore more active biomass as well as cells debris were produced. The higher d(MLSS)/(dt) at high OLR is due to the higher percentage of biomass produced meaning that more organic and non-biodegradable matters were fed into the reactor.

It can be concluded that for an MBR system operated under the same circumstances of this study, SRT within the range of 25–35 days would be applicable for the wastewater of the strength within the range of low and medium strength, since the MLSS increases in a low rate during the operation cycle (sustainable time). However, for wastewater with high strength, SRT should be lower than 25 days to reduce the rate of MLSS increase.

3.2. Dissolved oxygen and aeration rate

The results of dissolved oxygen (DO) and aeration rate show that the effect of the organic loading rate on aeration rate and DO concentration was very significant. For instance, comparing the results of trial 1 (low OLR) with those of trial 3 (high OLR) shows that the aeration rate in trial 1 was 20 l/min corresponding to DO of above 4 mg/l, whereas, the rate of aeration in trial 3 increased rapidly till 60 l/min corresponding to DO of below 2 mg/l. Similarly for other trials, it is noted that the higher the organic loading rate, the higher would be the aeration rate and correspondingly the lower the DO concentration. This implies that for higher organic load, a higher rate of aeration is required to obtain the same DO. On the other hand, to operate MBR with a high organic load means that more energy is required. Generally, the results of this study showed that for the low OLR trials the aeration rate varied from 6 to 12 m^3/m^2 membrane area per hour and the DO varied from 3.7 to 5.7 mg/l, whereas for the high OLR trials the aeration rate and the DO varied from 6 to 18 m^3/m^2 membrane area per hour and 0.9 to 4.4 mg/l, respectively. This depends on the concentration of MLSS in the reactor.

3.3. Removal of chemical oxygen demand (COD)

The results of COD for the low and high strength wastewater trials are shown in Fig. 3. The hydraulic retention time (HRT) during the sustainable flux was 8.1 h. The average feed COD for the low strength wastewater trials was 619 mg/l and the corresponding OLR was 1.73 kg COD /m^3.d (Table 3). Fig. 3a shows that the permeate COD for trials 1, 4, 6 and 9 ranged from 0 (undetectable) to 24, 8 to 16, 0 to 16 and 24 to 32 mg/l respectively, and the corresponding average removal efficiencies were 98.6, 98.5, 99.2 and 95.8%. The higher permeate COD values within individual trials were related to the relatively higher feed COD.

The average feed COD for the high strength wastewater trials (Fig. 3b) was 2500 mg/l (OLR = 6.82 kg COD/m^3.d). The permeate COD was constant at 8 mg/l for trial 3 while it ranged from 0 to 16, 8 to 16 and 16 to 24 mg/l for trials 5, 7 and 8 respectively. The corresponding average

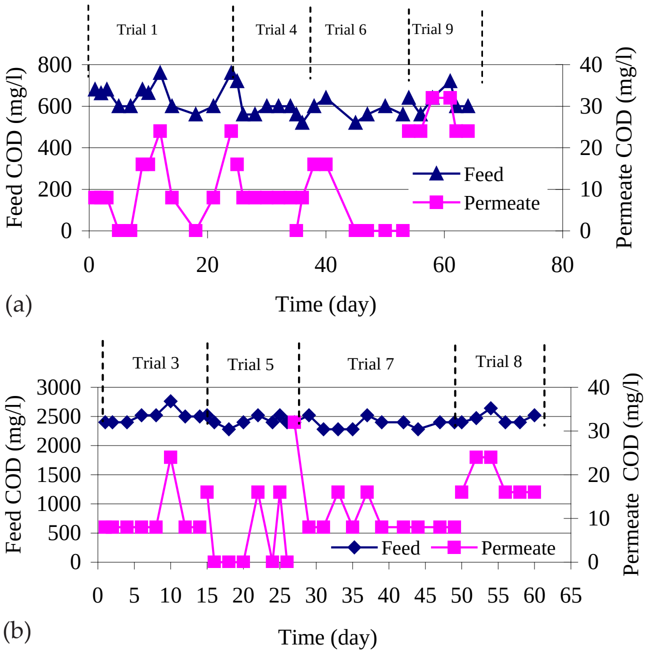

Fig. 3. Variation of COD with time (a) low strength wastewater and (b) high strength wastewater trials.

removal efficiencies for trials 3, 5, 7 and 8 were 99.6, 99.8, 99.2 and 99.2% respectively. It is observed that on day 10 of trial 3 the permeate COD increased to 24 mg/l, and this could be attributed to the high feed COD concentration on that day — 2760 mg/l. Similarly, the high permeate COD concentrations for trials 5 and 8 could also be related to the corresponding high concentrations of feed COD.

Several studies have been carried out on the removal of COD from municipal wastewater by using MBR [18–23]. In general, the feed COD for those studies varied between 100 and 870 mg/l and COD removal efficiency was between 95 and 99%. In the present study, the feed COD ranged between 520 and 2760 mg/l and COD removal efficiency ranged from 95.8 to 99.8%. So it can be concluded that the present study has treated higher strength municipal wastewater compared with those mentioned in literature, and the removal efficiencies of COD was also comparable with those reported by the other researchers.

3.4. The interaction effects of SRT and T_f on the COD removal

From Fig. 3a it can be seen that the highest permeate COD was obtained from trial 9. Similarly, from Fig. 3b, the highest permeate COD was obtained from trial 8. Both trials were carried out under high SRT and T_f. This implies that under this operating condition, the COD removal efficiency decreased. This reduction in efficiency could be related to the rate of biomass (d(MLSS)/(dt)) which was found to have increased at higher SRT (Table 4), therefore, more soluble microbial products (SMP) were produced.

This SMP could have contributed to the final permeate COD increasing its concentration.

From section 3.3 it can be seen that the removal efficiency of COD is very high for all operating conditions (higher than 98% except trial 9 which is 95.8%). However, the optimum conditions for the removal efficiency of low strength and high strength wastewater were achieved at trial 6 (99.2%) and trial 5 (99.8%) respectively. The two trials were operated at different conditions (Table 4), indicating that for different strength wastewaters, the removal efficiency can be obtained at different operating conditions. Generally, under the studied conditions, the interaction effects of SRT and T_f was found to be insignificant since the removal efficiencies in all cases were close to each other.

3.5. The effect of OLR on COD removal

Table 5 shows the permeate COD of low and high OLR for the trials conducted under similar operating conditions. It is noted that the average value of COD for the high OLR is either equal to or less than that of the low OLR (except trial 6 and 7). This indicates that in spite of the high increase of the influent COD (high OLR), the membrane bioreactor rapidly copes with alternating influent COD. This is due to the rapid increase in biomass concentration as mentioned in Section 3.1. This finding of the current study is consistent with those of Holler and Trösch [18], who found that with increasing OLR (COD 400–900 mg/l), the COD of the filtrate remained at low values.

3.6. Ammonia removal

Fig. 4 presents the results of ammonia nitrogen of feed and permeate for both low and high strength wastewater trials. The average ammonia nitrogen of the feed for the low strength trials was 19.4 mg/l and the corresponding volumetric loading rate (VLR) was 0.07 kg NH_3-N/m^3.d. The average permeate NH_3-N for trials 1, 4, 6 and 9 were respectively 8.723, 0.034, 0.119 and 0.242 mg/l, while the corresponding average removal efficiencies were 59.1, 99.8, 99.1 and 98.3%.

The results show that the removal efficiency of NH_3-N for trial 1 differed markedly from the other trials. This

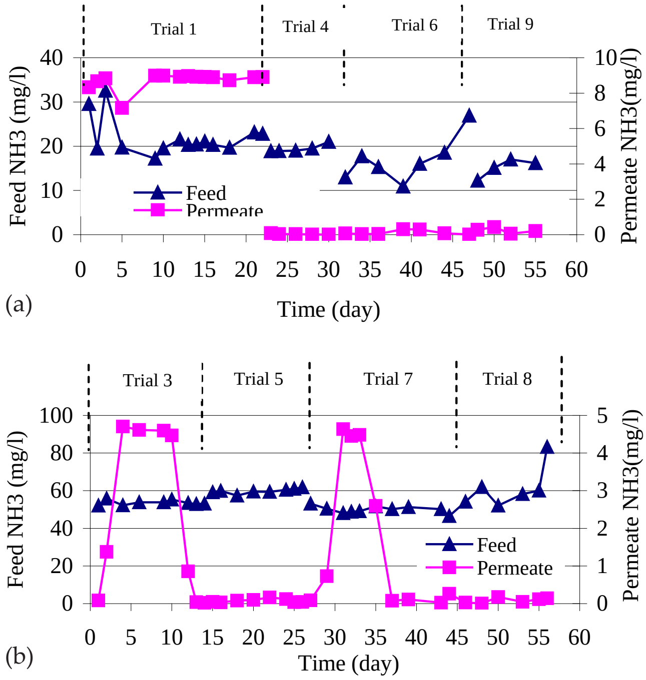

Fig. 4. Variation of ammonia with time (a) low strength wastewater trials and (b) high strength wastewater trials.

can be attributed to the high COD/N ratio and low pH of this trial are comparable with the other trials. Because the average pH value in the aeration tank for this trial was 7.31 whereas it varied between 7.88 and 8.20 for the rest of the trials. This was due to a mistake made in the preparation of the synthetic wastewater at the beginning of this study. The high COD/N ratio substantially influenced the nitrification process because it directly influenced the growth competition between autotrophic and heterotrophic microorganism populations [24,25]. The influence of COD/N ratio on the system nitrification capacity can be quantified by means of nitrification rate or nitrifying biomass fraction [26]. Harremoës and Sinkjaer [27] reported an increase in autotrophic biomass fraction from 1.5 to 2% when the influent COD/N ratio decreased from 3.4 to 2.6 g COD g N^{-1}, while Carrera et al. [26] found that a nitrification rate at 25°C was between

Table 5
Permeate COD for low and high strength wastewater trials

Trials of the same conditions		Operating conditions		Permeate COD (mg/l)	
Low level	High level	T_f (°C)	SRT (d)	Low OLR	High OLR
Trial 1	Trial 3	High	Low	10	10
Trial 4	Trial 5	Low	High	9	6
Trial 6	Trial 7	Low	Low	5	12
Trial 9	Trial 8	High	High	27	16

0.14 and 0.029 g NH_4^+-N g VSS^{-1} per day, with influent COD/N ratio of 0.71 and 3.4 g COD g N^{-1} respectively.

pH is also a key operation parameter on the nitrification process. The optimal pH for nitrification is around 8, whereas the values below 6.5 can suddenly decrease nitrification rate [29].

The average feed ammonia concentration for the high strength wastewater was 55.4 mg/l with an average VLR of 0.2 kg NH_3-N/m^3.d. It is observed that the ammonia concentration of permeate for trial 3 was 0.083 mg/l on the first day of the run and then it increased rapidly up to around 4.5 mg/l. After that it decreased rapidly to less than 0.1 mg/l after day 11. Similarly in trial 7, the ammonia concentration of permeate was as low as 0.088 mg/l during the first three days, after that it increased rapidly up to 4.5 mg/l and subsequently it decreased rapidly to less than 0.1 mg/l. With regards to trials 5 and 8, the concentrations of the respective permeate ammonia were kept constant at average values of 0.08 and 0.11 mg/l.

The rapid increase of the permeate ammonia concentration for trials 3 and 7 can be traced back to the DO concentration in the reactor. It was observed that DO for trial 3 was 2.3 mg/l on the first day, after that it decreased rapidly to 1 mg/l due to the rapid increase in MLSS concentration, and then it increased to above 2 mg/l due to the increased rate of aeration. The same behavior of DO concentration is observed in trial 7. However, it had stabilized above 2 mg/l throughout trials 5 and 8 although it decreased to around 1 mg/l for the first 3 days but it did not affect the results even though the literature revealed that the concentration of the DO required for the nitrification is 2 mg/l [17,28].

The average removal efficiencies for trials 3, 5, 7 and 8 were 95.7, 99.9, 96.1 and 99.8% respectively. The overall ammonia removal shows an average efficiency between 95.7 and 99.9% with an exceptional case of trial 1, where the permeate ammonia concentration was below 0.2 mg/l if the sudden increase in concentration is neglected.

3.7. Effect of the operating parameters on nitrification process

It can be observed that the performance of the MBR for ammonia nitrogen removal under the different operating conditions was very high. Even though the effect of the SRT ant T_f could not be observed clearly from Fig. 4, the two parameters had an indirect effect on the system as they significantly affected the biomass growth and consequently the DO concentration, which appeared to be an important factor in the nitrification process. The optimum removal efficiencies of ammonia nitrogen for the low and high strength wastewater were obtained at trial 4 and trial 5 respectively. Both trials were operated under high SRT and low T_f (Table 5). This could be due to the fact that under the high SRT more nitrifying bacteria would grow increasing the rate of nitrification. The effect of SRT seems to dominate the process.

Comparing Fig. 4a and 4b, it can be seen that the effect of OLR on nitrification is significant since high OLR led to a high consumption of DO, which in turn influenced the nitrification process significantly. Therefore, operating MBR at this range of OLR, SRT of 25 days and above could not be economically feasible, and a lower SRT should be considered to reduce the concentration of MLSS and accordingly to reduce the aeration rate.

3.8. Variation of pH under different operating conditions

The average value of the pH of feed, aeration and permeate tanks as well as the percentages of the pH increase in both aeration tank and permeate tank are presented in Table 6. The results show that the pH increased in the aeration tank under the different conditions of operation and the average increase varied from 14.9 to 23.3 % of the feed pH value. It is also observed that the permeate pH also increased under different treatments but its values were higher than those of the aeration tank and the average increase ranged between 1.6 and 4.2%.

The increase of the pH value in the aeration tank could be due to the removal of the acidic compounds by microorganism activities. Moreover, the slightly higher values of the permeate pH from that of the aeration tank could be due to the removal of small amount of acidic compounds by the membrane/cake layer around the membrane surface. This late process could take place just before the permeate pass through the cake layer and the membrane pores.

Fig. 5 shows the correlation between the feed pH and the percentage of pH increase in the aeration tank for both low and high strength OLR trials. The increase in pH in the aeration tank was negatively correlated with the feed pH. Pertaining to this, the R^2 for the low and high OLR trials were 0.8336 and 0.9106 respectively.

In this study, the results show that the final effluent pH values (permeate pH) under the different operating conditions did not exceed the permissible limit of standard A

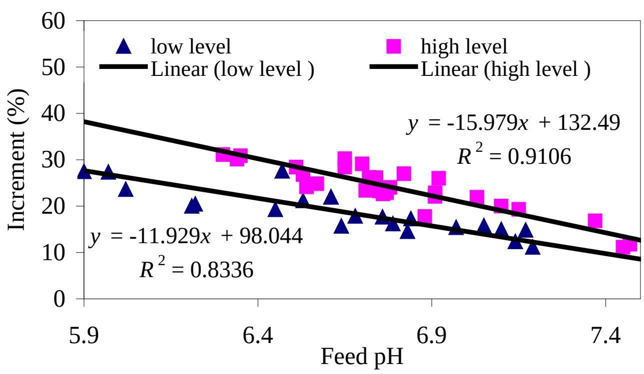

Fig. 5. Correlation between feed pH and the pH increase in the aeration tank.

Table 6
Average values of pH for different units and the percentage of increase in pH value

Level	Trial	pH			Increase in aeration (%)	Difference between aeration and permeate (%)
		Feed	Aeration	Permeate		
Low	1	5.98	7.31	7.61	22.8	4.2
	4	6.79	7.88	8.15	16.2	3.4
	6	6.76	7.96	8.12	17.8	2.1
	9	6.95	8.20	8.34	18.2	1.7
Medium	2	6.81	8.23	8.54	20.8	3.8
	10	7.33	8.40	8.54	14.9	1.6
High	3	6.81	8.29	8.47	22.0	2.5
	5	6.76	8.32	8.61	23.3	3.0
	7	7.25	8.48	8.75	17.5	3.1
	8	6.70	8.55	8.75	21.3	2.9

of the effluent discharge standards for Malaysian inland waters in which pH value should range between 6 and 9.

4. Conclusions

The rate of increase in MLSS (d(MLSS)/(d*t*)) and the MLVSS/MLSS were found to increase with higher SRT as well as higher OLR. Thus, for low OLR trials, the MLVSS/MLSS varied from 75.3 to 82.3% and d(MLSS)/(d*t*) from 87.5 to 297.3 mg/l.d, whereas for high OLR trials, MLVSS/MLSS varied from 80.4 to 83.7% and d(MLSS)/(d*t*) from 1355 to 2120 mg/l.d.

For higher OLR, a higher aeration rate was required to fulfill the DO demand. Therefore, for the low OLR trials, the aeration rate varied from 6 to 12 m^3/m^2 membrane area per hour and the corresponding DO varied from 3.7 to 5.7 mg/l. However, for the high OLR trials, the aeration rate varied from 6 to 18 m^3/m^2 membrane area per hour with a corresponding DO of 0.9–4.4 mg/l.

Under the different conditions tested, permeate COD, and NH_3-N were found to be in the range of 0–32 and 0.004–0.856 mg/l respectively. The interaction effects of SRT and T_f on COD removal found to be insignificant since the removal efficiencies in all cases were close to each other. Increasing OLR did not reduce the COD removal efficiency. This can be attributed to the rapid increase in biomass concentration. The optimum removal efficiency of ammonia nitrogen for the low and high strength wastewater was obtained under the condition of high SRT and low T_f, can be related to increasing growth of bacteria at higher SRT. Increasing OLR influenced the nitrification negatively, since high OLR led to a higher consumption of DO.

The pH increased significantly in the aeration tank and this increase was well correlated with the feed pH with R^2 of 0.8336 for low OLR trials and 0.9106 for high OLR trials. The pH increase in the aeration tank could be attributed to the removal of acidic compounds by the microorganisms.

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