

# Application of membrane bioreactor technology in treating high strength industrial wastewater: a performance review

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## HIGHLIGHTS

- ▶ Membrane bioreactor is a biological and filtration process combination.
- ▶ MBR is good in treating high strength industrial wastewater.
- ▶ Membrane bioreactor's main constrain is membrane fouling.
- ▶ Fouling mechanisms lead to membrane fouling.
- ▶ Fouling mitigation consists of physical, chemical and combination of both.

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## ABSTRACT

This paper reviews the performance of MBR in treating high strength industrial wastewater. The scope covers the operation, constraints and mitigation of the system in general views. High strength wastewater can be successfully treated by using membrane bioreactor (MBR) in different conditions according to the types and characteristics of wastewater and also MBR parameters operational control. High strength wastewater contains fats, oil and grease or other organic or inorganic compounds in great amount according to the types of sources that take part. Several factors need to be taken into consideration during the operation such as hydraulic retention time (HRT), solid retention time (SRT), mix liquor suspended solid (MLSS), food to microorganism (F/M), transmembrane pressure (TMP) and flux. Fouling factors need to be taken seriously because they are the major problems affecting the performance of the MBR and quality of the effluent. There are specific methods to reduce and clean the clogging membrane depending on the level of severity of the fouling. Besides that, the performance of MBR in removing soluble organic waste can be increased by adding a fouling reducer such as powdered activated carbon (PAC).

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**Abbreviations:** BOD5, Biological oxygen demand; CASP, Conventional activated sludge plant; EMBR, Extractive MBR; Flocc, Suspended solid particle of the mixed liquor; Flux, Volumetric flow rate per unit membrane area (LMH or m/d); F/M, Food per microorganism; FS, Flat sheet; HF, Hollow fiber; HRT, Hydraulic retention time (the time taken for the liquid phase to pass through a tank); iMBR, Immersed MBR; MABR, Membrane aerated biofilm reactor; MBR, Membrane bioreactor; MF, Microfiltration; Mixed liquor, The material formed in the bioreactor, containing biomass and other solids; MLSS, Mixed liquor suspended solids; NF, Nanofiltration; PAC, Powdered activated carbon; Permeability, Flux per unit TMP; PE, Polyethylene; PES, Polyethylsulphone; PP, Polypropylene; PVDF, Polyvinylidene; sMBR, Sidestream MBR; SMBR, Submerged MBR; SMP, Soluble microbial product; SND, Simultaneous nitrification denitrification; SRT, Solids retention time: the time taken for the solid (particulate) phase to pass through a tank; TKN, Total Kjeldahl nitrogen; TMP, Transmembrane pressure (Pa); TOC, Total organic compound; TSS, Total suspended solid (mg/L); UF, Ultrafiltration.

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## 1. Introduction

A desirable treated wastewater is water that is not only low in organic or mineral contaminants, but also free from biological entities such as bacteria, pathogens, and viruses. Therefore, treatment processes that are reliable, cost efficient and effective in removing a wide range of pollutants are required. One very promising technology involves the utilization of membrane bioreactor (MBRs). There are numerous successful pilot scale studies; some full scale units are in use in various parts of the world. For instance, the first large installation was in the United States, with a full scale external membrane MBR system for industrial wastewater treatment at the General Motors Plant in Mansfield, Ohio in early 1990s [1]. In 1998, the first large scale internal membrane MBR system for the treatment of industrial food ingredients wastewater was installed in North America [2]. According to the global market for MBR, the growth rate is over 10% annually due to the ability of MBR which is amazingly effective in removing the contaminants and in some cases, MBR is ideal for wastewater reuse applications [3]. There are more than 2200 MBR installations in operations or under construction worldwide and most of them are for municipal wastewater treatment. In North America, 11% of the installation of MBR worldwide and Zenon are larger installations as compared with Kubota and Mitsubishi. In Asian market for MBR, especially Japan and South Korea, the small scale for domestic wastewater is applied [4].

Bioreactor acts as a biological treatment processor and the membrane is used as a filter in the filtration process. Despite its reputation of being a reliable treatment process, the interest in MBR has slowed down for the past three decades mainly due to the high cost of membrane and membrane maintenance. The cost of the membrane has inclined together with the growth of membrane technology and the MBR technology is becoming more acceptable for industrial applications. In 1990s, submerged MBR was commercialized and it was found that this system had low operational cost [5] than any other types of MBR. Generally, the biological process shows a greater performance than the filtration process [6]. The membrane plays a role in separating solid and liquid whereby the biological process by activated sludge converts the particle waste into flocs before it is separated by the membrane.

MBR has its own capabilities that bring industries to choose MBR in treating high strength wastewater. MBR is known as an alternative for conventional activated sludge (CAS) treatment. CAS is different from MBR where settleability is negligible with the presence of membrane application. MBR also can give high performance in treating water besides having less footprints compared to conventional activated sludge where secondary clarifier processes are eliminated. MBR also produces high quality effluent [7], good in removing organic and inorganic contaminants, capable to resist high organic loading [8] and has lesser sludge generation [5]. Due to the advantages of MBR, some industries reuse treated water for other processes, for instance, industrial sanitary and landscape purposes. In some other cases, the MBR treated water is reused for heat integration and processing by ensuring the water treated by MBR has a lesser amount of contaminants to avoid sensitive equipment or pipes from breakdown [9].

The membrane fouling becomes a major factor since membrane is used and it is still under research to reduce the problem caused [10–13]. Apart from that, high cost maintenance and operation are

needed to maintain the performance of MBR and most of the treatment plants avoid using MBR because of this problem. Other constraints of concern are the limitations in pH, temperature, pressure and also some corrosive chemicals [5,9,14] that would lead to not only contaminate the microbes in the reactor but also destroy the membrane. However, through some researches, the membrane life can be prolonged [15–18] by limiting the constraints. Recently, some researches on modifications and integration of MBR have been done to minimize the constraints [17–19]. According to the environmental regulations and to decrease water consumption, this technology is actively manipulated and a lot of new MBR types exist to make sure that the treated water meets the standard and follows the reused water standard. MBR has been installed worldwide and the most common manufacturers are Kubota and Mitsubishi from Japan, Zenon from Canada. Zenon has the technology in treating wastewater which is four times better in performance compared to Kubota [9]. The challenges during handling MBR are to create the optimum condition to operate MBR for high strength wastewater and shock loading rate and also to control the fouling effect and reduce energy consumption during operations [5].

## 2. High strength industrial wastewater characteristics

High strength industrial wastewater is difficult to define. It can be different from food industries and chemical industries. Summer (2003) stated that high strength wastewater is defined as the wastewater that contains fats, oil and grease or other organic or inorganic compounds in great amount according to the types of sources that take part [20]. Basically it is called high strength because the components in the wastewater are in huge amount; for instance, high amount of COD [21], ammonia, suspended solid or heavy metal [22] and sometimes shock loading will happen. According to Mara and Horan (2003), the standard for substances for instance phenol, toluene, sulfides, cyanides and heavy metal should be set at very low limit, otherwise excessive amount will lead to oxygen depletion in water, besides being inhibiting and toxic to the biomass due to the disruption of enzyme and protein cells. However, some heavy metals are micronutrients and are required in small amount for organisms' metabolic function [23].

Wastewater strength can be leveled through the biodegradability characteristic of wastewater. BOD<sub>5</sub> is measured based on the quantity of oxygen that will be required to biologically stabilize the organic matter present, besides to measure the efficiency of some treatment processes in 5 days. COD is to measure oxygen equivalent to the material in wastewater including organic and inorganic materials that can be oxidized chemically in 2 h. General industries seldom use BOD test as daily analysis due to the long period of time required to get the result and a pre-treatment is needed when dealing with toxic waste; otherwise COD test is usually used. BOD corresponds with COD to measure the 'hardness' of wastewater or biodegradability and usually is done in preliminary operation. Strength of wastewater can be based on the biodegradable and non-biodegradable elements contained in the wastewater. High ratio of BOD<sub>5</sub>/COD is shown as readily biodegradable, otherwise low ratio BOD<sub>5</sub>/COD indicates as slowly biodegraded or contains a part of non-biodegradable or toxic elements. Furthermore, to treat wastewater with low BOD<sub>5</sub>/COD ratio, the slow biomass acclimatization may be required for

stabilization [24]. Durai and Rajasimman (2011) stated that 0.3 BOD<sub>5</sub>/COD ratio for tannery wastewater is low as compared with domestic wastewater ratio, 0.5 because it contains BOD<sub>5</sub> inhibitors [25]. Samudro and Mangkoedihardjo (2010) stated that biodegradability is a measurement of allowable level of organic matter that can be used as indicator to know the level of wastewater [26]. This ratio describes the biodegradability level of materials in which organic matter containing wastewater is readily broken down into the environment. Besides that, this ratio shows the level allowable of organic matter to degrade by biomass [26]. Generally, BOD<sub>5</sub>/COD 0.5 is considered as readily biodegradable or easily treatable [24]. Kumfer et al. (2010) for example, showed biodegradability greater than 0.5 for spent caustic wastewater after treatment by using wet air oxidation (WAO) [27]. If the ratio value is less than 0.5, the wastewater needs to have physical or chemical treatment before a biological treatment takes place [26,27]. Table 1 shows the characteristics of high strength wastewater for different industries. The biodegradability ratio for textile industries and tannery is low as compared with food industries due to high content of 'hard' COD/BOD<sub>5</sub>.

Wastewater that is originated from industries is considered as high strength wastewater. Industries prefer to use COD because it covers organic and inorganic substances and also to get instant result. There is no specific range to differentiate between low, medium and high strength of wastewater in the industries. In areas of biodegradable wastewater for instance, COD is deemed as low strength level when it is less than 1000 mg/L [28]. For example, even though petrochemical has 1000 mg/L COD, it is considered high strength level but for food industries, 1000 mg/L COD is considered as medium strength. This is because chemical industries contains 'hard' COD or high contain non-biodegradable compound, for example heavy metal as compared to food industries which normally contain high content of biodegradable compound, for instance nitrogen or phosphorus elements [21].

A study that was carried out by United Nations [38] has shown that pipelines and equipment in industrial sectors such as cooling water, boiler water, process water and irrigation and maintenance and landscape face a big problem when in contact with high strength wastewater. It can cause clogging, corrosion, scaling, biological growth and foaming in any systems. It can also happen especially when the high strength wastewater is discharged into the environment that clogs the soil.

Usually, treated wastewater would be discharged into the environment, or some of the industries would reuse treated water or sell it to other industries. The treated water needs to meet the standard that has been stated in the environment regulation; for instance in Malaysia, the industries need to comply with the Environmental Quality Act 1974 where parameters limiting the effluent in Third Schedule are provided, otherwise fines will be charged [39].

### 3. A typical MBR processes configuration

In CAS treatment, large clarifying basins are needed to make sure the flocs are completely settled but by using membranes, there are no more settling processes needed and the area used for clarifier can be eliminated besides acting as a separator [40]. Fig. 1 shows the basic schematic diagram of MBR configuration. Fig. 1a shows an immersed membrane bioreactor (iMBR) or submerged membrane bioreactor (sMBR) module. Fig. 1b shows a side-stream or external membrane module while [40,41]. For sMBR system, the feed wastewater is directly in contact with biomass. Then, both wastewater and biomass are pumped through the recirculation loop consisting of membranes. The concentrated sludge is recycled back to the reactor while the water effluent is discharged. The purpose of separating the membrane and bioreactor is actually to reduce the power used by the air diffuser [42].

The operational cost of iMBR system is less because there is no recirculation loop compared with the sMBR system. A biological process occurs around the membrane. Both need to pump out the excess sludge to maintain sludge age. The pressure driven across the membrane on these systems can either be by suction of the membrane or applying a pressure to the bioreactor. Radjenovic et al. (2008) stated that pressure-driven filtration is used in sMBR and vacuum-driven is used for iMBR, which operates in dead-end mode [9]. Air bubbles are supplied to both systems for aeration besides scouring, especially for the immersed system in reducing membrane fouling in cross flow effect across the membrane surface [7,12]. There are also aerobic and anaerobic MBR where oxygen acts as an important medium for the microbial growth in the aerobic process whilst anaerobic is done without oxygen. Anaerobic MBR is less efficient in removing COD and takes a long time to start up. Usually, anaerobic treatment is used for treating high strength wastewater at low temperature which is suitable for microbial growth. It is difficult to adjust low temperature for the waste feed. Besides that, it causes high fouling compared with aerobic at low flux [41].

Fig. 2 shows three different processes of membrane bioreactor that have been modified according to the types of wastewater, which are (Fig. 2a) MBR biomass separation, (Fig. 2b) membrane aeration bioreactor or also called membrane aerated biofilm reactor (MABR) and (Fig. 2c) extractive MBR (EMBR). However, MABR and EMBR are applied in a pilot scale for industrial wastewater. MABR directly uses purified oxygen without bubble formation for biofilm growth on the external side of membrane. The organic matters are biodegraded within the biofilm under aerobic condition and the oxygen supplied is almost 100% utilized for biodegradation. EMBR is normally operated for high concentration of inorganic compounds, for instance, high salinity and extremely pH value that can inhibit the

**Table 1**  
Characteristics of High Strength Wastewater for Different Industries.

Industry	COD (mg/L)	BOD (mg/L)	COD/BOD	NH <sub>4</sub> -N (mg/L)	TSS (mg/L)	SO <sub>4</sub> <sup>2-</sup> (mg/L)	PO <sub>4</sub> <sup>3-</sup> (mg/L)	Oil (mg/L)	Phenol (mg/L)
Tannery [29]	2000	-	-	-	-	400	-	-	-
Tannery [21]	16,000	5000	0.313	450	-	-	-	-	-
Textile [30]	6000	700	0.117	20	-	-	120	-	-
Textile [31]	4000	500	0.125	4.8	-	200	2	-	-
Dyeing [32]	1300	250	0.192	100	200	-	-	40	-
Textile [33]	1500	500	0.333	50	140	-	7	-	-
Wheat starch [2]	35,000	16,000	0.457	-	13,300	-	-	-	-
Dairy [21]	3500	2200	0.629	120	-	-	-	-	-
Beverage [21]	1800	1000	0.556	-	-	-	-	-	-
Palm oil [18]	67,000	34,000	0.507	50	24,000	-	-	100,000	-
Pet food [34]	21,000	10,000	0.476	110	54,000	-	200	-	-
Dairy product [35]	880	680	0.773	-	2480	-	-	-	-
Phenolic [36]	797	-	-	131	-	-	-	-	37.3
Pharmaceutical [37]	6300	3225	0.51	-	-	-	-	-	-

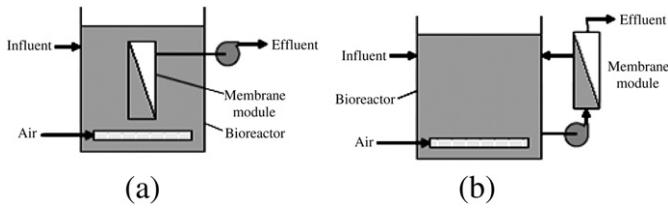


Fig. 1. Schematic of MBR (a) submerged membrane module and (b) side-stream external membrane module [40].

biodegradation process. EMBR selectively extracts specific organic pollutants (i.e. phenol, hydrogen sulfide and some inorganic) that can be degraded in separated bioreactor [43]. MBR biomass separation is commonly used.

### 3.1. Membrane characteristic

The ability of the membrane depends on the size of pores, types of materials, types of wastewater to be treated, solubility and retention time. Retention is observed due to the concentration change between the retentate (a part of solution that cannot cross over the membrane) and permeate (solution after filtration). Permeability, flux, pressure (TMP) and resistance are the parameters that also need to be considered while conducting MBR. Permeability is flux per pressure ( $J/\Delta P$ ) or LMH/ $\Delta kPa$ . Flux (LMH) is the flow of permeate per unit of membrane (ability of the component accessible to the membrane) and it is related with hydraulic resistance, thickness of the membrane or cake layer and driven force. Driven force is the gradient of membrane potential area (unit area of the membrane) of mass transport that involves pressure and concentration of particles. The mass transport mechanism for the membrane depends on the structure and materials of the membrane. Membrane structure plays an important role in transporting mechanism whether the structure is parallel or in series. Diffusion and solubility of the component are related to the kinetic ability of the mass transport for membrane. The solution dissolves into the membrane and separates between retentate and permeates. For the membrane itself, pore-size membrane participates in kinetic mass transport. [44].

The types of membranes used are different depending on the size of contaminants contacting during the treatment process. Basically, contaminants with the size of a particle from 100–1000 nm use microfiltration (MF) for removing suspended particles; ultrafiltration (UF) for particle size 5–100 nm, for instance bacteria and virus; and nanofiltration (NF) for particles with size 1–5 nm for dissolved particles. In treating high strength wastewater with shock loading of matter, microfiltration is chosen among the others due to prolonging the membrane usage. Most of the treatment plants use MF or UF instead of NF regarding the fouling and cost factors [5,9,12,41].

Two types of materials that are commonly used to construct the membranes are polymeric and ceramic. Ceramic membrane is usually

used by industrial wastewater which has a good performance in filtration compared to polymer due to its high chemical resistance, inert and easy to clean [45–47]. The chemical stability depends not only on the materials used but also the size of pore where it reduces the stability of the membrane when the structure is too fine. Ceramic also has higher hydrophilic ability due to the water contact angle. However, the main issue of ceramic membrane is it is very expensive to fabricate and is fragile [46]. The suitable polymers that have been used commercially include PVDF, PES, PE and PP because of good physical and chemical resistance. Polymer membrane (porous membrane) has its own weakness where it can foul easily because of its hydrophobic characteristic. The hydrophobic membrane is used because it easily fabricates its pore size. However, the hydrophobic membrane weakness can be improved by coating the membrane using hydrophilic polymer [48]. PE is more quickly to be fouled compared to PVDF [5]. Membrane configurations also play an important part where for every configuration, they have their own advantages and disadvantages based on the cost, capability to stand in turbulence and back-flushable (normally suitable for HF membrane) [41].

There are two types of operations which are dead-end and cross-flow operation that have been shown in Fig. 3(a) and (b). Both need to be operated with the presence of pressure driven (TMP). Dead end is filtered perpendicularly to the membrane surface. The solids from the feed which are greater than the pore size are easier to deposit on the membrane surface. Most dead-end processes are in batch process [49]. Cross-flow is liquid flow parallel towards a filter surface and transports suspended particles of membrane surface by permeating flow due to pressure drop. Basically this type of filtration is carried out by using hollow fiber (HF), flat sheet (FS) or multi tubular (MT). Cross-flow filtration can reduce the formatting of the cake layer on the surface of the membrane [41,49].

Critical flux is an important parameter that needs to be considered during MBR operation. It is a value of flux that exists as irreversible deposit. There is no fouling below the critical flux. Critical flux happens when a thick cake layer forms on the membrane. Fouling could happen when the flux is above critical flux. From critical flux, the suitable flux for the operation can be defined based on the TMP sustainability. There is no standard method used to find the critical flux due to the difficulties during reporting data. There is one practical method that can be used which is the flux-step method that is shown in Fig. 4. The highest flux can be determined when the flux is increased and there is no TMP increment. It is shown when fouling is about to happen. The Eqs. (1) to (4) below are to define the fouling performance for each flux-step [50]

$$\text{Initial TMP increase : } \Delta P_0 = TMP_f^n - TMP_i^{n-1} \quad (1)$$

$$\text{Rate of TMP increase : } \frac{dP}{dt} = \frac{TMP_f^n - TMP_i^n}{t_f^n - t_i^n} \quad (2)$$

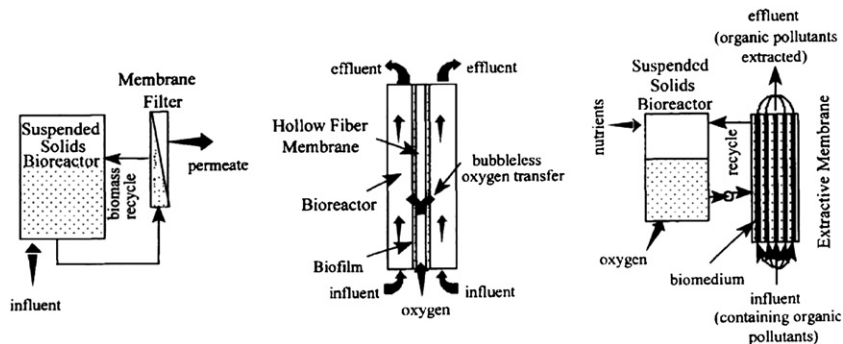


Fig. 2. Types of MBR processes (a) MBR Biomass separation and (b) Membrane Aeration Bioreactor and (c) Extraction MBR [43].

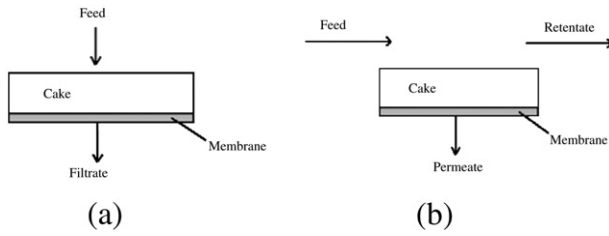


Fig. 3. (a) Dead-end filtration and (b) Cross-flow filtration [49].

$$\text{Average TMP} : \frac{TMP_f^n + TMP_i^n}{2} \quad (3)$$

$$\text{Permeability of the system} : K = \frac{J}{P_{avg}} \quad (4)$$

From the equations, the relationship between the fouling rate ( $dP/dt$ ), permeability ( $J/dP$ ) and flux is plotted. The critical flux is intersected between permeability and fouling rate line [51]. Fig. 5 shows the intersection between permeability and fouling rate intersection.

### 3.2. Biomass characteristic

Biomass in activated sludge from industries is heterogenous. Basic nutrients of biomass are glucose, nitrogen and phosphorus with ratio 100:5:1 in weight. The domination of biomass can occur through the acclimation process and this depends on the major constituent of feed wastewater. CASP has been used for a long time. However, when related with high strength wastewater, this method will not be able to cope with the high content of organic loading and inorganic matter because of low biodegradability and inhibitory and in some cases [53], it can destroy the microbes because of shock loading of matters. This is because microbes take a long time to biodegrade the matters and need high concentration of biomass (MLSS) to make sure all the organics be totally biodegradable. Basically, SRT is operated coupled with HRT for CASP. SRT is the solids or flocs growth in many sizes that need to be retained in the plant before it is settled down for a period of time where HRT is the time taken for the matters to pass through the plant. This means that CASP relies on both to make sure the flocs are really settled before going into other treatments [41]. Also, CASP needs biomass with fast growth and flocs formation species. Otherwise, if the biomass has a low growth rate, it will lead to washing out together with the excess sludge because of the shortage of SRT. Consequently, the production of sludge and F/M ratio is high and ends up with high sludge excess and disposal covering around 50 to 60% over the total cost of wastewater treatment [9].

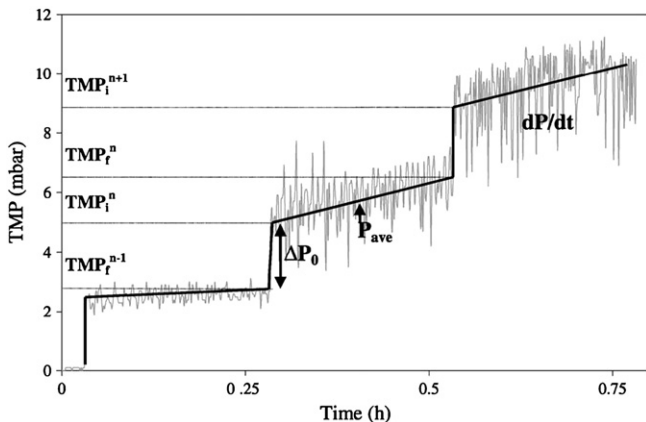


Fig. 4. Flux-step method [50].

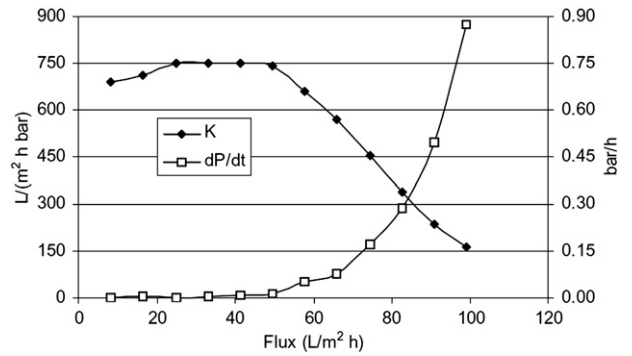


Fig. 5. Relationship between permeability, fouling rate and flux to critical flux determination [52].

In order to get the best performance in treating high strength wastewater, the MLSS must be high to enhance the degradation process. Nonetheless, in MBR system, high concentration of MLS hastens the membrane fouling [54]. However, as compared to other systems, SRT and HRT in MBR system do not depend on each other because MBR is more on the membrane filtration rather than settling by gravity. Also, this system does not consider the flocs growth but still maintains the minimum sludge production with low F/M ratio (less substrate is presented per unit of biomass) [9,40,55] and retaining the biomass in the reactor and sludge age [6,41,56,57]. Besides that, the formation of flocs makes it easier to filter. However, if F/M is too low, the biomass in the activated sludge could not grow well [6], or else if MBR has very high MLSS it will lead to clogging, low efficiency of aeration and it needs a large bioreactor (increasing the initial capital cost) [9]. HRT with low level will increase organic loading rate (OLR) which will end up with reactor volume reduction and reduce the performance of MBR; whereas if the HRT is high, MBR has a good performance [58–60].

Other studies show the correlation between SRT and formation of SMP and EPS. Increased SRT will decrease SMP and EPS whereby the biomass will stay longer in the reactor and prolong the biological degradation process; otherwise, if SRT is lower, it will increase the level of SMP and fouling [58,61,62]. Other studies show vice versa [62]. Pollice et al. (2008) stated the result from a respirometric test showing the MBR could be operated at higher SRT without drawbacks on the biodegradation activities. The efficiency of organic removal depends on SRT due to the reduction of mixed liquor in SMP. There is no consensus recommended for SRT operation range. However, SRT is dependent on the nature and recalcitrance of the wastewater pollutants, and to achieve long SRT is by lowering the F/M ratio. Other method to identify MBR steady state with high SRT is by stabilizing MLVSS under the same condition for few days. MLVSS stabilization is a consequence of the selected F/M and HRT [59]. In nitrification cases where nitrifying autotroph, which is known as slow-growing bacteria, has slowly dominated in the system when SRT is increased. It showed that long SRT is potential to shift the microbial population from one to another microbial population that brings advantages to the system [41]. Huang et al. (2001) has stated to get a complete nitrification process, and 10 days of SRT was required [63]. MBR is well operated at high SRT with the decrease of sludge production (g MLVSS/g COD) [62]. Nevertheless, if SRT takes too long, it will tend to foul the membrane with the accumulation of matters and high viscosity of sludge [58].

Furthermore, the slow operating rate leads to long HRT and large volume of reactor. Nitrifying bacteria operate more slowly than carbon degraders and to achieve complete nitrification, a longer HRT was required [41]. Normally, MBR has SRT more than 30 days as compared with CASP in a range of 5 to 30 days. In addition, MBR has low value of loading rate or F/M ratio which is less than 0.1/d as compared to CASP 0.05–1.5/d due to high concentration of MLSS [30]. Viero and

Anna (2008) discussed that HRT is closely related with reactor volume and operational cost. Treatment industrial wastewater by using MBR may present some challenges due to some pollutants being slowly biodegraded. Qin et al. (2007) reported that in reducing the HRT from 19 to 13 h, the removal efficiency increased in short-term operation (1 week) but the intermediate HRT gave the worst result [64]. It is different from industrial wastewater which generally requires higher HRT due to complex pollutants degradation and gives longer biomass adaptation period [59]. In anaerobic membrane bioreactor, HRT and SRT are independent and also produce methane as a side product and odor [41] whereas they do not use any aeration process and energy saving. Besides that, methane can be collected as energy generation [65].

#### 4. MBR operations for the treatment of high strength wastewater

During an MBR operation, there are different operating conditions depending on the level of constituents of high strength wastewater. The operational conditions cover the sludge behaviors (e.g. MLSS, DO, SRT and HRT) and membrane behaviors (e.g. membrane configuration and pore size). Table 2 below shows the operational parameters according to the types of industries. These two types of industries are chosen because of the difference in biodegradability ratio. By referring to Table 1, both industries are categorized as having produced high strength wastewater but they are different in terms of biodegradability. Textile industries have low biodegradability as compared to food industries due to the slow biodegradable organic or toxic matters present [26]. Food industries are known as producing high strength organic wastewater and the level of biodegradability is high due to the high content of readily biodegradable organic matters [66].

##### 4.1. Textile industries

In textile industries, the primary source of wastewater is spent dye and rinsing water that contain low biodegradability, toxicity and

color issues. Most textile industries apply biological treatment, chemical precipitation, adsorption and membrane technology [33].

Hai et al. (2005) applied hollow fiber membrane with 50 to 200  $\mu\text{m}$  pore of membrane for treating high strength wastewater from synthetic textile industries consisting of various chemicals, organic loading and color. In this study, white-rot fungi *Coriolus versicolor*, NBRC 9791 were used in order to remove specifically color and other nutrients. The reactor was under the working volume of 12.5 L with two HF-FS membranes and each membrane had surface area of 0.2  $\text{m}^2$  and 0.4  $\mu\text{m}$  (Mitsubishi Rayon). The two membranes performance were compared under different operating fluxes (0.05–0.3  $\text{m}^3/\text{d}$ ) and maintained other operational condition (e.g. 8000  $\text{mg}$  MLSS/L and 0.01  $\text{m}^3/\text{s}$  of aeration) of the color and the TOC removal was 97% to 99%, respectively [10].

Badani et al. (2005) showed the best performance with 15,000  $\text{mg}/\text{L}$  of MLSS. The average color removal was 70%. The TMP was increased and the flux decreased due to membrane fouling. The HRT of 2 days was sufficient to degrade COD up to 97% of removal in 15,000  $\text{mg}/\text{L}$  of MLSS for a long term performance [30]. Brik et al. (2006) stated that at the beginning of the process, the sludge 5000  $\text{mg}/\text{L}$  of MLSS was treated with municipal wastewater before being acclimatized with textile wastewater. The MLSS was increased from 5000 to 10,000  $\text{mg}/\text{L}$  and was continuously increased until 15,000  $\text{mg}/\text{L}$  before the sludge withdrawal. In this study also, it was observed that the effect of nutrient addition did not give much contribution to improve the COD removal. However, there were some disadvantages of adding the nutrient which contributed in the conductivity because of the inorganic content in the additive nutrient and severe fouling occurred [31]. A study from Yigit et al. (2009) investigated highly concentrated mixed textile wastewater and from the study, it was reported that the influent  $\text{BOD}_5/\text{COD}$  ratio was 0.32 and it was dominated by slowly biodegradable and biorecalcitrant organics. From the result, the removal showed a successful performance of SBR and it could be concluded that colonies of biomass with a wide spectrum of degradation capability were able to degrade as readily biodegradable, slow biodegradable and biorecalcitrant. The mechanisms of color removal basically used biodegradation and adsorption onto solid [33].

**Table 2**  
Operational parameters according to the types of industries.

	Textile			Food			Refinery	Pharmaceutical	Municipal
	Textile [30]	Textile [31]	Textile [33]	Pet Food [34]	Palm Oil [18]	Dairy Product [35]	Phenolic [36]	Pharmaceutical [37]	Heavy Metal [67]
Application	Laboratory	Laboratory	Pilot	Laboratory	Laboratory	Laboratory	Laboratory	Pilot	Laboratory
Reactor Volume (L)	500	20	230	20	20	20	4.4	10,000	210
Reactor Type	Aerobic, Side-stream	Aerobic, Side-stream	Aerobic, Submerged	Aerobic, Submerged	Aerobic, Submerged	Aerobic, Submerged	Aerobic, Submerged	Aerobic, Submerged	Aerobic, Submerged
Membrane Configuration	UF, (7 tubular modules), PVDF	UF, external tubular cross-flow, PVDF	HF	2 modules	FS, 1 module	MF, 34 strands of a HF	HF	HF, 4220 strands	HF, PVDF
Membrane Surface Area ( $\text{m}^2$ )	-	0.28	-	0.047	0.1	0.00162	0.00278	12.1 $\text{m}^2/\text{g}$	0.93
Pore Size ( $\mu\text{m}$ )	0.025	-	0.04	0.04	0.4	0.4	0.15	0.1	0.04
Flux ( $\text{L}/\text{m}^2\text{h}$ )	-	30	20	-	10	Horizontal: 5.03 Vertical: 2.27	15-17	0.384-1.536	22.3
MLSS ( $\text{mg}/\text{L}$ )	5000-15,000 $\pm$	-	13,900	-	5000 $\pm$	4000-10,000	10,000	6000-17,000	5840-10,330
MLVSS ( $\text{mg}/\text{L}$ )	-	-	-	47,000	-	-	-	-	-
DO ( $\text{mg}/\text{L}$ )	1-3 $\pm$	2-3 $\pm$	-	3 $\pm$	8 $\pm$	-	-	-	-
HRT (day)	2	0.7-4	0.58	2.9 $\pm$	0.8 $\pm$	-	10 $\pm$	1	10.3
SRT (day)	-	11	25	50	-	-	-	>40	15
COD Removal (%)	97 $\pm$	90 $\pm$	97	97 $\pm$	94 $\pm$	-	67	96	508-535
Color Removal (%)	70 $\pm$	98 $\pm$	98	-	-	-	-	-	-
TSS Removal (%)	-	-	99	-	-	99	-	-	226-267
TN Removal (%)	-	-	78	-	-	-	-	-	44-53
Phenol removal (%)	-	-	-	-	-	-	98	-	-

## 4.2. Food industries

From the environmental perspective, the majority of food processing facilities are characterized as very high organic strength wastewater generators. The major pollutant loadings are BOD, COD, TSS, fat-oil-grease and nutrients. Most industries employ on-site primary treatment prior to send their wastewater to municipal wastewater treatment plant [66].

Acharya et al. (2006) reported that with biodegradability below 0.5, the organic removal for high strength pet food wastewater by crossing the membrane for the first stage was 7 to 37% and 20 to 37% for the second stage. It was due to the retention of particles larger than the membrane pore size and it is supported by Huang et al. (2001) as (10 to 20% of COD removal across the membrane). This study also showed a mechanism of nitrogen removal in two stages of MBR treatment by developing simultaneous nitrification denitrification (SND) module. The model indicated that 21% of influent nitrogen was removed by SND, 31% by cell synthesis ( $N_{cell}$ ) and 13% by stripped ( $N_{stripped}$ ) at first stage of MBR treatment. Eq. (5) below shows the predicted model of nitrogen removal by SND [34].

$$NH_{4SND} = TKN_{in} - TKN_{out} - N_{stripped} - N_{cell} \quad (5)$$

Katayon et al., (2004) studied different configurations of membrane (horizontal and vertical) and different concentrations of MLSS affecting the performance of MBR. Even though the value of COD and BOD was low, the amount of TSS was too high. The result showed slow flux declining horizontally as compared vertically and by increasing the MLSS concentration, the permeate flux decreased. TSS and turbidity removal had good performance result at low MLSS concentration [35]. Palm oil is categorized under the agro-industry but it also encompasses food industry. Yejian et al. (2008) reported that the treatment of palm oil mill by using anaerobic expanded granular sludge bed (EGSB) and aerobic biofilm reactor (ABR) integrated with UF and reverse osmosis (RO) brought successful result. For the first EGSB, the COD removal was 93% and 43% of the organic matter was converted into biogas as recovery energy. However, in ABR, the COD removal only reduced 27% from the effluent of EGSB and UF removed 10% of COD from ABR. In RO, there were no COD detected. All suspended solid was captured by UF and the RO filtered dissolved solid and inorganic salt. It can be concluded that EGSB and ABR were used purposely to reduce the TSS and oil into a low degree to prolong the UF and RO membranes life [19]. Damayanti et al. (2011) studied on the influence of PAC, zeolite (Ze) and *Moringa oleifera* (Mo) as BFR on hybrid membrane bioreactor of palm oil mill effluent. The hybrid reactors consisted of anaerobic-anoxic-aerobic MBR. The MLSS and flux used were 15,000 mg/L and 11 LMH. The amount of COD feed was 35,000–45,000 mg/L with FS chlorinated polyethylene material membrane, 0.4  $\mu$ m membrane pore size, 0.1 m<sup>2</sup> membrane area per module and 3 modules were also used. This study was looking on the SMP removal and PAC showed a good performance, followed by Mo and Ze with 70%, 56% and 42% removal [17]. This performance will be discussed further in fouling mitigation.

## 4.3. Refinery, pharmacy and municipal

Viero et al. (2008) reported that phenolic wastewater can affect biodegradation when phenol is added. At first phase, the stream was treated without phenolic wastewater and the COD removal was 67%. At second phase, phenolic wastewater was added with ration 1:6, and COD removal was 61% and phenol removal 98%. When the ratio was changed to 1: 240 at third phase, COD and phenol removal were 58% and 99.3% respectively. The COD was insufficiently removed due to recalcitrant in the feed [36,59]

In Southern Taiwan, Chang et al. (2008) reported that 96% and 99% of COD and BOD removals are for pharmaceutical wastewater

respectively with mean value of biodegradability 0.5. In this study, the excess sludge was wasted in accordance with the sludge growth rate of SRT which was more than 40 days. According to Chang et al. (2008) there is a variation of MLSS that could be classified. At the beginning, MLSS growth rate increased slowly due to slow adaptation of biomass with operation condition. The biomass was stable when the MLSS growth rate increased drastically and for some reasons, the MLSS grow rate drastically increased due to high content of COD [37].

Katsou et al. (2011) studied on heavy metal treated by membrane bioreactor. The feed heavy metal concentration was ranged according to industrial wastewaters which were from 3.4–9.1 mg/L for copper ( $Cu^{2+}$ ), 3.9–14.7 mg/L for lead ( $Pb^{2+}$ ), 4.3–14.7 mg/L for nickel ( $Ni^{2+}$ ) and 3.2–12.1 mg/L for zink ( $Zn^{2+}$ ). The waste was fed 6 h time period in order to avoid excessive heavy metal accumulation inside the reactor. The vermiculate was added as metal ion adsorption to enhance the removal of heavy metal. The flux and backwash flux were maintained as 22.3 and 26.8 LMH respectively and operated at a steady state condition with 15 days of SRT and 10.3 h for HRT in 210 L of volume reactor. The result showed average removal as 80% of  $Cu^{2+}$ , 98% of  $Pb^{2+}$ , 50% of  $Ni^{2+}$  and 77% of  $Zn^{2+}$ . The value of COD feed average was  $500 \pm 10$  mg/L and the removal average was 80 to  $90\% \pm 5$ . The biomass toxicity can be lowered by maintaining pH at alkaline environment to enhance metal removal through precipitation. It can be concluded that the heavy metals can be removed by various processes which are (i) metal precipitation inside the reactor; (ii) biosorption of metal ions on sludge flocs (iii) retention of the insoluble metal species through UF membrane and (iv) adsorption of metal ions on vermiculite [67].

## 5. MBR application: challenges and constraints

Judd (2006) stated that cost is a major constraint to MBR technology in 1990s because of high cost of membrane which leads to the increase of maintenance and operational costs. Membrane cost covers on replacing the severe membrane fouling or corrupted membrane and membrane cleaning process during maintenance [5,41].

### 5.1. Membrane fouling

Fouling is a major part that needs to be considered when it comes to membrane. When dealing with high strength wastewater containing high load of contaminants, it will lead to high clogging of the membrane due to the membrane characteristics, biomass and operating condition. Fig. 6 shows the factors influencing membrane fouling during MBR operation. Fouling can be monitored through TMP and flux changes. The flux-step method sample result in Fig. 7 shows the correlation between TMP and flux at time interval of 15 min [41]. When the flux increases, TMP also increases. It shows that there is more wastewater that can be separated until the TMP drops when the flux continues to increase. Decreasing phase shows that membranes have a high resistance and need cleaning before the membranes become fouled which leads to membrane damage.

Fouling is the physicochemical interaction between the biofluid and membrane to form a cake layer and the adsorption of the dissolved particles into membrane pores and leads to flux decline. If a physical cleaning takes place, it is classified as reversible fouling. Irreversible fouling is due to the adsorption of the particles into the membrane and blocking the pore [68]. Fig. 8 shows the mechanisms of fouling dependence on particle size to the pore diameter [41]. The formation of cake which is inevitable on the membrane surface becomes one of the factors that lead to membrane fouling. In a general system, the side stream of MBR has higher fouling tendency than submerged MBR. This is because the side stream of MBR needs high energy of pumping that produces high flux that will lead to repeating the fouling compared with submerged MBR [41].

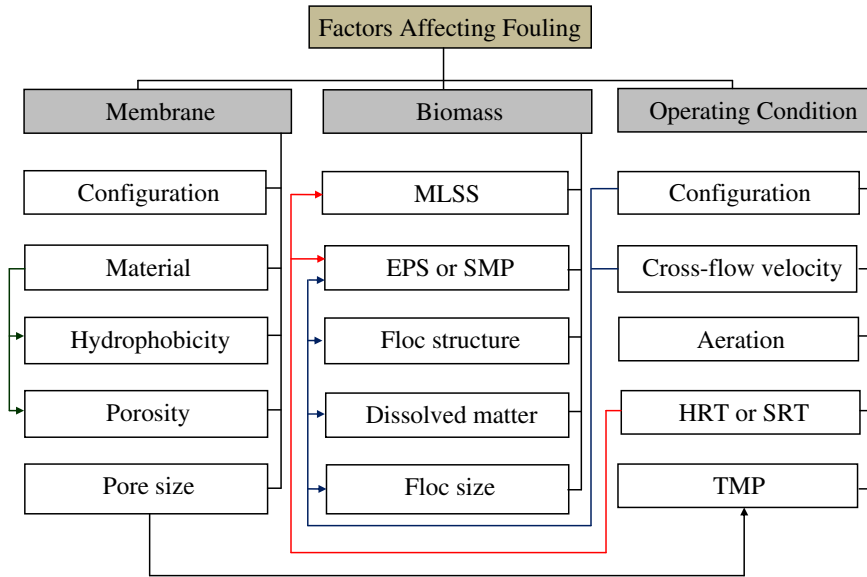


Fig. 6. Factors influencing membrane fouling in membrane bioreactor [68].

Eq. (6) shows the relationship between TMP and flux from the fundamental of Darcy's Law which becomes a benchmark in measuring the resistance of membrane, driving force for each unit membrane area and nearly fouling and the time for cleaning the membrane [41]. Eq. (7) is a resistance in membrane series model (RIS) with simple model to describe membrane fouling mechanisms [69].

$$J = TMP/(\eta \cdot R_t) \tag{6}$$

$$R_t = R_m + R_e + R_i = R_m + (R_p + R_c) + R_i \tag{7}$$

where

- $R_m$  is the constant resistance of the clean membrane.
- $R_e$  is the internal fouling resistance which includes  $R_p$  (resistance due to concentration polarization, which can be neglected) and  $R_c$  (the cake layer resistance)
- $R_i$  is the resistance due to pore blocking.

Choo et al. (1996) reported that sMBR with FS membrane had 0.5%  $R_m$ , 82.8%  $R_p$ , 16.1%  $R_{ef}$  (external fouling resistance) and 0.5%  $R_{if}$  (internal fouling resistance) in treated alcohol distillery wastewater for 200 days

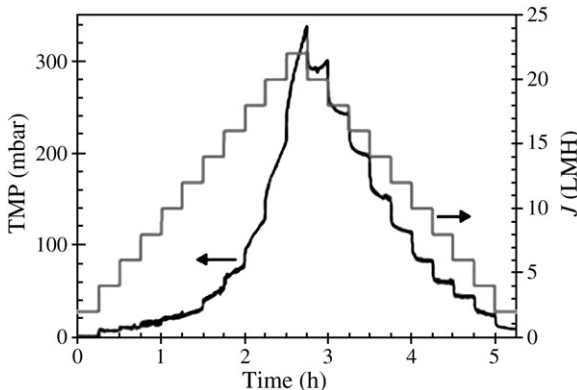


Fig. 7. Transmembrane pressure and flux versus time by flux-step method (adapted from [41]).

operation.  $R_p$  gave a large contribution to fouling due to colloidal solutes and macro molecular species accumulated onto the membrane [11]. Hai et al. (2005) in the study of textile industry stated that the mechanism of fouling happens because of the forming of cake layer of fungi and sticky starch. FS membrane was vulnerable to internal pore blocking but HF happened due to the presence of cake layer in the latter case [10]. Badani et al. (2005) stated that the membrane fouling depends on the extent of shear stress imposed to microbial flocs [70]. Manser et al. (2005) reported that flocs size from the MBR is ten times smaller than CAS. Since there was no selection for settleable flocs in MBR system, the biomass had no physical inducement to build large flocs that also could lead to membrane fouling [71]. Katsuo et al. (2011) stated that coarse bubble aeration cannot effectively remove deposits from the membrane surface. The suspended solid of the mineral from continuous operation could attach on the membrane surface [67]. Viero et al. stated that the soluble polysaccharides (PS) can be considered as an indicator of the fouling level since the increase in PS concentration tends to reduce the filterability [36].

5.2. Fouling mitigation

The membrane cleaning takes place when the flux is slightly dropped and the TMP increases drastically. There are three types of

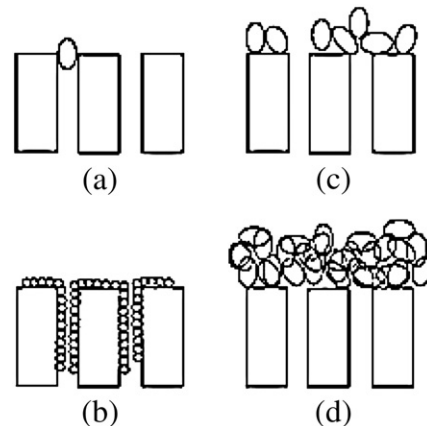


Fig. 8. Fouling mechanisms [41] (a) complete blocking, (b) standard blocking, (c) intermediate blocking and (d) cake filtration.



cleaning which are physical, chemical and a combination of physical and chemical. Physical cleaning includes backwash (only suitable for HF) and where the water effluent is pumped into the reverse direction but it is not suitable for FS membrane. Membrane brushing is also a method of the physical cleaning that can be applied in situ for FS membrane. It is a quick process but is less effective than chemical cleaning. Basically, physical cleaning only removes the coarse solid or cake on the surface of the membrane, but for chemical cleaning, it can remove the flocs. It can also remove strong matters that stick on the membrane's surface. It needs to be taken into consideration that energy consumption is applied for physical cleaning and almost 30% of permeate (effluent) is used for back wash. Blocher et al. (2002) stated that the purpose of chemical cleaning, besides for fouling elimination, is also for membrane disinfection [72]. For industrial purpose, in situ cleaning is usually performed if the fouling is not severe, otherwise ex situ takes place. Most of the studies showed that the first chemical used for membrane cleaning was sodium hypochlorite (NaOCl) [10,33,72,73].

From Hai et al. (2005), by referring to Fig. 9, stated there are two stages of cleaning where a, b and c are points of flux recovery. When the flux per unit pressure dropped, the cleaning process was recovered by in situ membrane brushing because air bubbles from diffuser could not fully scrub the fungi off from the membrane. The worst thing was that the air bubble diffuser pushed the fungi towards the membrane. The ex situ cleaning and sludge withdrawal were taken when the flux per unit pressure was almost zero. Table 3 shows the value of TMP after the membrane was cleaned by using water and chemicals [10]. Katayon et al. (2004) reported that with diffuser at the bottom of the reactor, the membrane configuration with horizontally placement minimized the membrane fouling as compared with the vertical one [35]. Yigit et al. (2009) reported that during operation, backwashing routine took over (15 s after each 10 min of permeate production) and when the TMP was 60 kPa, the first chemical backpulse was by using sodium hypochlorite. However, the ex situ cleaning (sodium hypochlorite with hydrochloric acid) was applied when irreversible foulants took place [33]. Membrane configuration also plays an important part to reduce fouling. In Katayon et al. (2004) study, it showed that horizontal membrane configuration produced slow permeate flux decline (slowly membrane to foul) as compared with the vertical one [35]. In general, the change in TMP over the course of a cycle should not exceed 60 kPa and according to this, chemical cleaning was applied every 7–14 days. It means that, the maximum allowable rate of pressure change was 60 kPa/week or 0.042 kPa/h [74].

Regular cleaning of the membrane shortens the membrane life and membrane change is needed when the membrane no longer can be used. Activated carbon (AC) is applied in MBR as a biofouling reducer (BFR) to prolong the membrane life. AC has the ability to adsorb organic and other pollutants besides becoming scrubber for membrane. Small sized and small pores of AC will have more surface area that increases the adsorption velocity. Between the granular and

**Table 3**

TMP value (kPa) after water and chemical cleaning (flux = 0.3 m/d) [10].

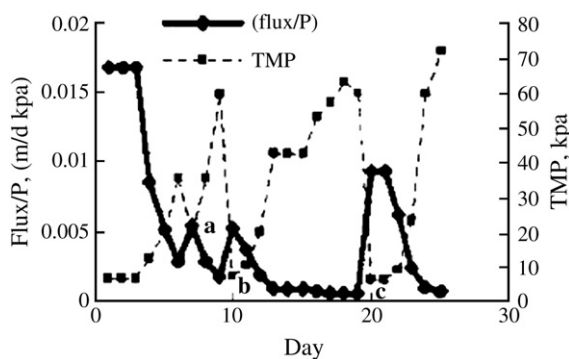
	Hollow Fiber	Flat-sheet
Initial	6	7
Fouling	65	86
Cleaning:		
Water	10	86
Chemical (NaOCl)	6	7

powder AC, powder has a higher adsorption [18] and is able to remove low molecular weight organic rather than granules because PAC has higher surface area. PAC also can be a medium for bacterial sticking and growth. As a result, biological activity would increase by sustaining the PAC in a reactor. Widjaja et al. (2010) used set-back flushing method for 10 min to increase the performance of MBR in treating shock loading of a toxic compound [6]. Biological degradation with added PAC gives better results compared to non-PAC because of their characteristics to adsorb the matters. Besides that, PAC can treat COD in shock loading by increasing the amount of PAC by stabilizing the shock loading performance [6]. Yuniarto et al. (2008) showed that by adding PAC, the performance of MBR increased up to 3.8% in removing high strength palm oil wastewater [18]. Damayanti et al. (2011) showed the performance of 3 types of BFR in removing SMP in palm oil mill effluent (POME) treatment. As stated before, PAC gave good performance followed by Mo and Ze. PAC existed as cationic polymers with the surface area 3000 to 4000 m<sup>2</sup>/g, as compared with Ze which ranged from 600 to 800 m<sup>2</sup>/g, and Mo which ranged from 713 to 744 m<sup>2</sup>/g. PAC enhanced the flux three times lower than without-BFR and successfully formed flocs by charging the neutralization mechanism from organic and inorganic components and enlarging the floc together to build up porosity in the cake layer [17].

Lee et al. (2007) in the study showed that the membrane fouling reducer, MFR, flocculated the activated sludge to reduce the cake layer on the surface of membrane. The result showed that in order to achieve 30kPa of TPM, a small amount of MFR was needed effectively in the removal of high contaminants in wastewater. MFR from cationic polymer acted as a positive charge and when it was added into the reactor, it would adsorb negative charge from the microbial flocs and changed into neutral charge. Then, the neutralized sludge floc attracted each other to form large flocs by a charged neutralization mechanism, which and is also called flocculation process. On the other hand, in high concentration of MFR over the optimum concentration, the surface turned into positively charged and the deflocculation began by a mechanism of electrostatic repulsion [75].

## 6. Conclusion

Majority of high strength wastewaters have been successfully treated by MBR and this has been demonstrated by the use of MBR in textile and food industries. Some indicators are used to define high strength industrial wastewaters. Wastewater characterisation is method to identify the 'hardness' of wastewater, for instance, the biodegradable (BOD<sub>5</sub>/COD) ratio towards viability of biomass in preliminary operation. By controlling the parameters such as SRT, HRT, TMP, Flux and MLSS to an optimum condition, the best performance of MBR can be produced. For wastewater with very high pollutant loading, it may need to be treated prior to entering MBR to avoid membrane fouling. However, there are some methods to reduce the fouling problems such as physical and chemical cleanings and also by using biofouling reducer (BFR) to enhance the performance of MBR. MBR can be developed and many researchers are aggressively modifying the MBR system based on wastewater conditions not only to increase the performance but at the same time reducing the operational cost. Membrane is the heart of this system; however, it

**Fig. 9.** TMP increase and flux decline [10].

is also sensitive to unusual chemicals besides pH, pressure and temperature that contribute to reduce the performance of MBR. These problems need to be of concern since the condition of wastewater changes depending on the processes and the environment involved. In some cases, modifications of the wastewater such as dilution for high strength and toxic wastewater or neutralization of acidic or base of wastewater need to be done to prolong the lifespan of the membrane besides maintaining the microbial growth.

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