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Fouling control strategy for submerged membrane bioreactor filtration processes using aeration airflow, backwash, and relaxation: a review

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ABSTRACT

As of today, the application of membrane bioreactors (MBRs) in wastewater treatment plants has become significantly important in various industries. The success of MBR is mainly because of the effective membrane technology used in this kind of reactor. However, membrane technology does not escape from several drawbacks, which includes high maintenance costs and fouling problems. In order to run a plant with both an optimum capability and cost, an in-depth understanding of the behavior of filtration systems is very important to the plant operator. In this paper, we review and have considered the fouling control techniques applied to submerged membrane filtration processes including hollow fiber membranes and flat sheet types of membrane filtration. The review covers the techniques involving operational parameters, such as aeration, backwashing, and relaxation. In addition, in this paper, the modeling techniques and available automatic control techniques, using stated parameters to control fouling in membrane filtration processes, are presented. The performance results of each technique are then discussed and reviewed.

Keywords: Submerged MBR; Fouling; Aeration; Backwash; Relaxation

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1. Introduction

In recent years, membrane technology has become significantly important in filtration systems in many applications worldwide and has become a requirement in wastewater treatment technology. With more stringent effluent requirements and environmental concerns, as well as water protection awareness, membrane technology is one of the promising techniques that can resolve these kinds of problems. Membrane filtration systems are usually combined with bioreactors that treat wastewater. The configuration of membrane bioreactors (MBRs) is divided by two well-known architectures which are the submerged membrane bioreactor (SMBR) and the side stream membrane bioreactor. The SMBR configuration deploys the membrane inside the bioreactor where the biological reaction takes place. The membrane types for these kinds of filtration systems are using either flat-sheet technology or hollow fiber types of membrane for microfiltration (MF) or ultrafiltration (UF) systems. The side stream model is also known as a side stream membrane bioreactor. In many wastewater filtration systems, a membrane filtration system is used to replace the settler, where the filtration only took place

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after the biological treatment. The configuration of an MBR filtration system is given in Fig. 1.

However, membrane technology does not escape from its well-known problem which is the fouling phenomenon. A fouling phenomenon is caused by many factors such as colloidal, particulate, and solute materials. Membrane fouling is a complex process, affected by many parameters including the operation, influent properties, and the membrane itself [1]. Fouling will affect the overall performance of a filtration system in the long run, by inducing incremental filtration resistance, as a result of the compact formation of fouling layer on the membrane surface. This will lead to a complete blockage of the process. Fig. 2 shows the fouling phenomena during a membrane filtration. This is where Fig. 2(a) represents the initial state of the filtration process when there is less blocking on the membrane surface. On the other hand, Fig. 2(b) shows the membrane filtration after a long time of filtration, and where the surface of the membrane starts forming, with both a fouling layer on the surface and inside the membrane pore. Fouling can cause troubles for the membrane bioreactor operator, which can lead to the increment of operating costs due to maintenance of the filtration system. This includes a removal of the fouling layer, cleaning, and in the worst case, it will cause damage to the membrane and that will need to be replaced.

The fouling phenomena in an MBR system cannot be avoided and one of the key indicators of a successful application of a membrane filtration system is measured by the effectiveness of a fouling control, without compromising the effluent quality. Currently, various physical cleaning techniques are employed in many pilot and full-scale membrane filtration processes globally. From an operational point of view, fouling can be controlled and can be reduced by using techniques such as an air bubble (aeration) control, relaxation, backwashing, and chemical cleaning. Even though these techniques cannot totally resolve a fouling problem, with an effective measurement and control system, they can be utilized to enhance the membrane's filtration performance. Fig. 3 shows a typical response of a membrane filtration system to the cleaning operation.

It is important to understand the effectiveness of the method when controlling fouling in a membrane filtration operation, because this approach will not be effective if the coordination of the method is not properly strategized. Each method employed has an

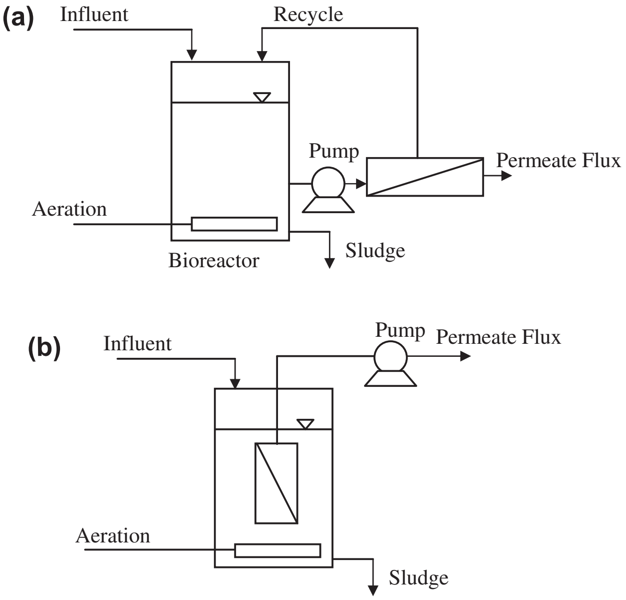

Fig. 1. (a) Side stream filtration system and (b) Submerged membrane filtration system.

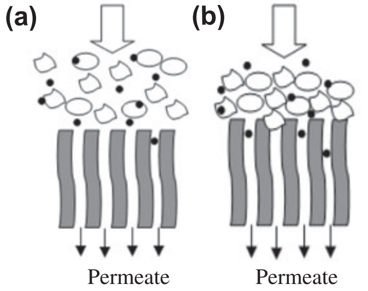

Fig. 2. (a) Membrane surface at the early stage of filtration and (b) Membrane surface at a later stage of filtration.

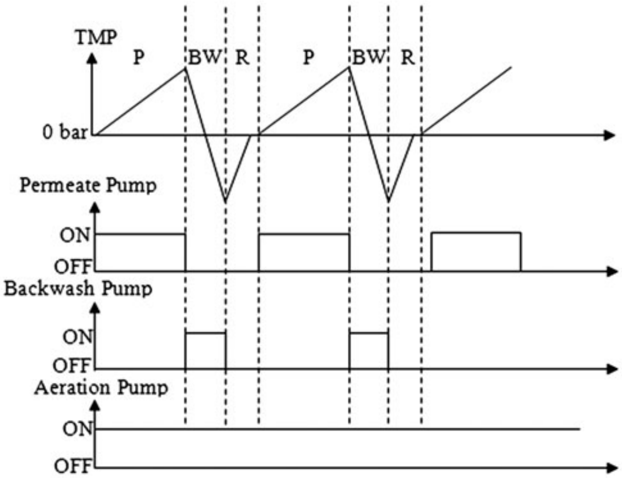

Fig. 3. Fouling control flow chart in a typical submerged MBR (permeate (P), backwash (BW), and relaxation (R)).

optimum condition to remove fouling. Without clearly understanding a suitable method, with an optimum operational performance, the operator will suffer from an inefficient filtration process and this can cause a high energy consumption [2].

This paper is organized as follows:

The second section will review the relationship of an aeration operation when attempting to control a membrane filtration optimization and the fouling therein. The third section covers a review on the operation of a backwash technique when rectifying a fouling development. The fourth section discusses a relaxation technique that is available in the literature and is related to a membrane filtration enhancement. The last section is a conclusion of the suitable techniques available and an efficient way of implementing all of the reviewed processes.

2. Fouling control using an aeration air flow process

An air flow through an aeration process is one of the popular methods when implementing a fouling control in an MBR system [3]. Aeration can disturb the polarized layer concentration that is formed near the membrane [4] and it has a correlation between the aeration air flow intensity and the fluxation flow rate [5]. However, an aeration process is found to have the highest energy consumption during an MBR operation [6]. Several works have been performed in order to optimally use the air bubbles. The study of an air bubble system is reported by Ndinisa et al. [7], and this has shown an improvement in fouling problems, however, this method has a threshold flow rate where the fouling resistance cannot be removed effectively. Similar results are shared by Lei et al. [8], where a dual-phase air flow can improve the flux, and too high an air flow does not have any significance with respect to the flux recovery. In addition, when varying the intensity of the air flow rate, an aeration-controlled strategy can also be implemented by the ON and OFF stage of the aeration supply. From an experiment conducted using a flat sheet-submerged MBR as related by Vera et al. [9], they found that an aeration frequency of 10 s ON and 10 s OFF was the most optimum setting for their hollow fiber MBR, while no improvement was shown when the frequency was increased further. An aeration effect on fouling has been found to be more effective during an idle cleaning time, when compared to the permeation time. Thus, a good scheduling must be performed in order to ensure that there is energy efficiency during an MBR operation [10]. Different aeration zones were introduced by Guibert et al. [11], where the aeration input was located in different locations around the membrane filter, and the aeration input point was turned ON and OFF, according to the selected zone. This method is now compared with conventional continuous aeration processes with fixed location aeration. Based on fouling rate measurements, the authors found that the proposed method improved the fouling development in an SMBR system. The effect of a cyclic aeration system, for the fouling control in an SMBR wastewater treatment, was studied by Wu and He [12], where a comparison study was conducted between a constant and a cyclic aeration. The authors observed that the fouling rate in the cyclic aeration mode was higher, when compared with constant aeration, due to reduced air in the low aeration stage. However, a lower irreversible fouling was found in the cyclic aeration mode. Other advantages of cyclic aeration were a better flux recovery when compared with constant aeration.

Among popular techniques when using aeration for fouling control is air sparging. An experiment conducted by Delgado et al. [13] studied the sheer intensity for fouling removal in a submerged MBR system. The experiment was conducted with differently mixed liquor-suspended solids (MLSS) and showed that the air sparging technique can effectively remove the cake layer fouling rate, despite the less significant effect on residual fouling. An air sparging technique was also found by Chang and Judd [14], where two types of coarse bubble aeration modes were studied. The first one was an air lift mode where air was injected into the membrane tube channels. The other technique was using an air jet mode where intermittent sparging was introduced. When comparing these two modes, the air lift mode was able to increase the flux by 43%; however, a gas flow exceeding 10 liters per minute (LPM) showed no further improvement in the flux. On the other hand, an air jet mode suffers from clogging due to the slow accumulation of sludge. However, by applying a constant backwash system, it was observed that the permeability in the air jet mode is more than in the air lift mode. Another research on an air sparging technique was done by Posh and Schiewer [15], where the work covered a long-term experiment on air sparging techniques in an effort to prevent membrane fouling for glucose-based syntactic waste water. This technique was shown to be reliable when improving the permeation flux and the prevention of any fouling development. Meanwhile, Lei et al. [16] studied the combination of air sparging intensity and the intermittence of aeration, and they were both found to be effective in fouling reduction and flux enhancement. However, optimum air intensity must be obtained in order to provide efficiency in energy utilization and fouling removal effectiveness. Continuous bubbling was also suggested by Tian et al. [17] to be more effective in preventing a fouling rate's rapid development when compared to intermittent bubbling at the same air flow rate. The optimum frequency of pulsating needs to be determined in order to ensure sufficient bubbles, since any excessive bubbles will decrease the efficiency, and hence, be ineffective for the fouling control system [18]. On top of that, an experiment conducted by Zhang et al. [18] also highlighted the importance of bubbling size and an optimum aeration flow rate, in order to influence the hydrodynamics of a flat-sheeted SMBR.

Besides air sparging intensity, the air sparging configuration may also affect membrane fouling. Park et al. [19] studied three phases of air sparging configuration and their effect on membrane fouling. Phases one, two, and three, respectively, represent the simultaneous upward and downward air sparging technique; the single upward air sparging technique; and the simultaneous upward and downward air sparging technique. Each of these techniques was implemented for 68, 37, and 55 d of experiment, respectively. The performances of the above-mentioned techniques were measured based on the increasing rate of TMP, the declining rate of permeating flux, fouling resistance, and an irreversible fouling coefficient. The authors found that simultaneous upward and downward air sparging was the most effective way for fouling control. The membrane position was identified by Cheng and Lee [4] of having a major impact on the aeration effectiveness in fouling removal. The authors found that by inclining the membrane position from 90° to 160°, the aeration effectiveness was improved, since a low aeration speed was sufficient to remove fouling in the 160° position.

In an aeration fouling control strategy, the air bubble size must not be compromised. The effect of the bubble size has been studied by Ndinisa et al. [7] and they have shown that a different nozzle size of diffuser can affect fouling development. The larger the nozzle, a bigger bubble is produced, and hence, the effectiveness to control fouling is much higher. However, in [17] and [20], it was shown that a smaller bubble is more effective for flat-sheet membranes. A comparison study between the two regimes of bubbling techniques was conducted between free bubbling and slug bubbling for antifouling strategies on a flat-sheet SMBR. From the experiments conducted, it was found that the slug bubbling technique yields a better antifouling improvement for both higher flux and moderate flux during a long-term experiment [21]. In addition, the slug bubbling technique can also save on the overall aeration energy utilized, because only a low aeration speed is required in order to remove the fouling layer when compared to the free bubbling technique. Recently, an aeration application in a closed loop control system is receiving more attention from researchers. An advanced controlling technique in submerged membrane filtration processes, for instance, has been practiced extensively in the last 10–15 y. A fuzzy logic control (FLC) arrangement is one of the popular methods in a membrane filtration system, since the application of a model-based filtration process is very difficult to manage [22]. Several of the literatures on FLC show that the ability of a controller is able to improve fouling in filtration processes. For instance, works by Huyskens et al. [23] used three inputs and one output FLC to optimize the filtration process. The three inputs were a reversible fouling measure (VFMrev) from the fouling sensor, temperature, and flux. Converting these values into a percentage universe of discourse, the output of the controller is the aeration rate of supply to the membrane reactor. The result shows that the developed FLC can improve the fouling slope from rapid fouling to an acceptable fouling rate.

The application of a knowledge-based control has also attracted researchers in membrane filtration system fouling controls. The application of this type of controller has shown promising results in controlling fouling, and has shown an energy efficiency in membrane filtration processes as discussed by the researchers in [24–26]. The controller development only used a permeability slope value to decide upon the action of the aeration, without any sophisticated sensor, hence, reducing the overall costs. However, in a controller development, the designer must understand the dynamic performance of a filtration system. Apart from that, an in-depth knowledge of actuator effectiveness is highly required, in order to prevent rapid fouling. Fig. 4 shows the effect of aeration intensity to the permeating flow and the membrane's permeability.

From this result, it can be shown that there is a linear relationship between the permeant flow and the aeration air flow. Besides that, the linearity between the flux and the aeration demand was also discussed by Guglielmi et al. [27] for multi-tube and flat-sheet membranes. However, an energy model developed by Verrecht et al. [6] emphasized that the linear relationship of the air flow and the permeant flow remains linear, until a threshold aeration flow rate is reached, where a further intensity of aeration shows significant permeant flow and fouling reduction. Another work by Bouhabila et al. [28] stated that an increment of air flow rate from 1.2 to 3.6 m^3/m^2 can reduce the total resistance by a factor of 3 and can increase the flux to 13 LPH m^2.

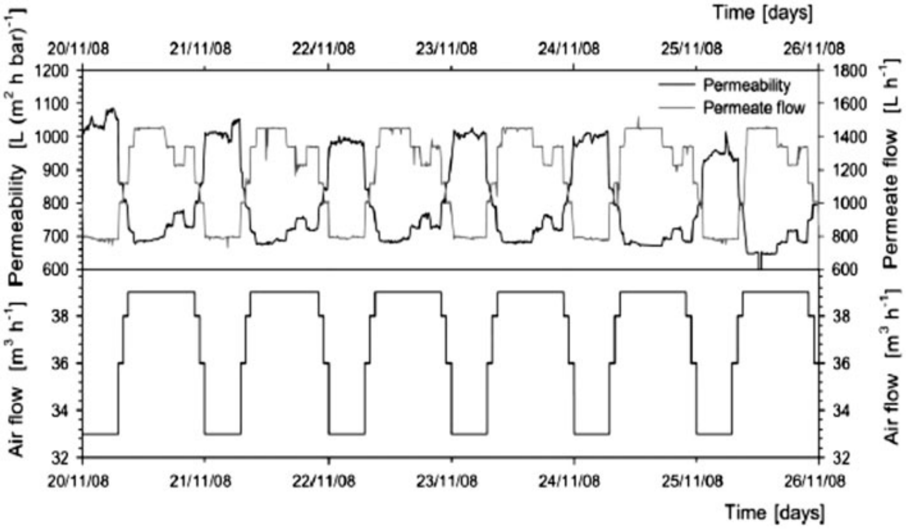

Fig. 4. Effect of air flow intensity on the permeant flow and permeability [26].

A study of aeration on the biological effects related to fouling has been conducted by Ji and Zhou [29], and they have shown that an increased aeration causes the protein/carbohydrate to decrease. The research showed that there is a correlation between protein/carbohydrate with regard to fouling phenomena. Apart from that, a study by Lim et al. [30] showed that an aeration ON/OFF time has a significant impact on membrane fouling, where a large OFF time and a small ON time will cause ESP and carbohydrate to increase. A microbial activity was also found to be affected by a low oxygen condition, where the concentration is high and it occurs in the OFF aeration stage. Table 1 shows the aeration setting for membrane cleaning.

3. Fouling control using a backwash operation

Backwashing is another important mechanism in membrane filtration fouling control [28]. A standard definition of backwashing is the reversing of permeation back through the membrane [2]. However, a backwash can be conducted by using methods other than permeation, and this includes chemicals, air,

Table 1
Aeration air flow setup for membrane cleaning

Refs.	Membrane type	Plant scale	Air flow rate/SAD	Remarks
Ndinisa et al. [7]	Flat sheet	Lab	12 L/min	Continuous aeration technique
Vera et al. [9]	Hollow fiber	Pilot	0.55 N m^3/h m^2	Intermittence aeration
Wu et al. [12]	–	Lab	15–30 L/h	Cyclic aeration technique
Delgado et al. [13]	Hollow fiber	Pilot	3.7 m^3/h m^2	Continuous aeration technique
Tian et al. [17]	Hollow fiber	Lab	5.0 m^3/m^2 h	Air bubble technique
Park et al. [19]	Hollow fiber	Pilot	0.020 m^3/m^2 h	Upward and downward technique
Ivanovic et al. [31]	Hollow fiber	Pilot	1.68–3.37 N m^3/m^2 h	Continuous aeration technique
Zhang et al. [21]	Flat sheet	Lab	2.5 L/min	Slug bubbling
Wang et al. [32]	Hollow fiber	Pilot	400–500 L/m^2 h	Continuous aeration technique
Guglielmi et al. [27]	Flat sheet	Full	0.88 N m^3/m^2 h	Continuous aeration technique
Lorain et al. [33]	Hollow fiber	Pilot	190 NL/m^2 h	Sequential aeration technique
Rahimi et al. [34]	Hollow fiber	Pilot	0.8–1.2 m^3/m^2 h	Continuous aeration technique
Low et al. [35]	Hollow fiber	Lab	8–12 m^3/m^2 h	Intermittence aeration
Bilad et al. [36]	Flat sheet	Pilot	24.8–75.5 N m^3/m^2 h	–
Zsirai et al. [37]	Hollow fiber	Full	0.12–1 N m^3/m^2 h	–

Note: SAD – Specific aeration demand.

clean water, and other mediums that can remove fouling. An effective backwash scheduling can optimize a filtration process by preventing internal fouling. A backwash cleaning method can only be successfully implemented if the factors that influence the implementation are considered such as the backwash flux intensity, the instantaneous flux, a permeate to backwash ration, and the type of backwash agent used in the cleaning process. Fig. 5 shows the most influential factors reported to affect a backwash process.

Any optimized backwashing scheduling is usually done by trial and error and is based upon the experience of the operators. The effectiveness of fouling removal by using a backwash technique can be measured from Eq. (1):

$$\text{Reversibility } (\%) = \frac{\text{TMP}_{\text{i}}^{\text{Final}} - \text{TMP}_{\text{i+1}}^{\text{initial}}}{\Delta t} \quad (1)$$

Where $\text{TMP}_{i+1}^{\text{initial}}$and $\text{TMP}_{i}^{\text{final}}$ are the initial and final TMP values of the filtration cycle i, respectively, and Δt is the filtration duration of each cycle.

From a survey conducted by Wang et al. in [38], they found that a backwash frequency can be divided into two groups, which are (a) less frequent, but with a longer backwash and (b) a frequent backwash, but with a shorter backwash duration. The authors also found an interesting fact where a full-scale MBR plant survey by Itokawa et al. [39] showed a more frequent backwash, and when compared with literature surveys, where a full-scale municipal treatment plant had their backwash around 5–50 s per 3.33–8.33 min filtration. Usually, exhaustive experiments are done in order to obtain the optimal filtration flux [40]. A study of backwash strength and backwash duration was conducted by Akhondi et al. [41]. In this study, the TMP value was used as an indicator of fouling development in the membrane and the contribution of this kind of an operation to the consumption of energy. At the end of the study, it was shown that backwash duration does not linearly improve the fouling removal, as the permeation flow drops when the backwash duration is increased from 2 to 3 min. However, the result indicated that backwash duration can affect the number of filtration cycles. In terms of backwash strength, the authors found a similar result where the strength of the backwash did not show any significant improvement on the fouling rate.

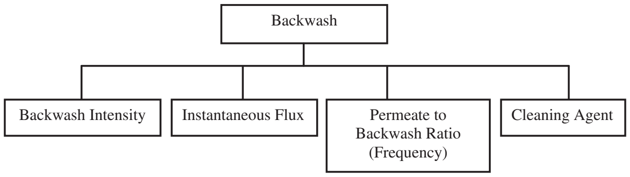

Fig. 5. The influential factors in a backwash performance.

Another similar study was done by Wu et al. [42] where a different backwash time, the strength and backwash-to-permeant ratio were used to study the fouling dynamic behavior in an aerobic MBR system. The research indicated that a duration of 40 s, with a 480-s interval, was the most effective scheduling, where the schedule gives the lowest TMP value after 24 h of running duration. These results revealed that a higher duration of backwash did not give much improvement to the fouling rate. When comparing the backwash strength with a similar duration, the authors concluded that the strength was more significant in fouling removal when compared to a backwash duration. In addition, a similar finding was reported by Zsirai et al. [37], where an increment of back flush flux was more effective when compared with an increase in back flush duration. Meanwhile, a model to predict the minimum backwash duration required in order to reverse the flow through a membrane was developed [43]. A series of experiments using a submerged hollow fiber MBR were conducted in order to develop a prediction model. It was shown that when trapped or dissolved air released, owing to a drop in pressure during permeation through a membrane, it can have a significant effect on backwashing that is used to remove fouling deposits.

Another study on backwash frequency was reported by Jiang et al. [44]. In this work, three sets of permeation and backwash schedules were used with all of the given sets having a similar permeation-to-backwash ratio. However, the duration of the permeation and backwash time for Set 2 and Set 3 had a two and three times higher ratio, respectively, when compared to Set 1. From the 24-h experiment's duration, Set 1 had the highest increment of irreversible fouling, followed by Set 2 and Set 3. The result showed that a less frequent backwash decreases the amount of irreversible fouling. The authors also concluded that reversible fouling can be effectively removed by backwashing below a certain amount of permeation flux.

The effect of backwashing to a ceramic tubular membrane in a submerged MBR configuration has been studied by Hwang et al. [45]. In this study, other parameters such as duration, flux, and filtration time were also included. Various backwash durations have been tested in order to investigate fouling effects. An increment in a backwash duration led to a higher productivity when the operation was shorter than two minutes. Back pumping of more filtrate for a longer backwash duration causes the productivity to decrease. The optimal operating conditions in such a submerged filtration system were determined to be a filtration duration time of 30 min and a backwash time of two minutes, with a backwash flow rate of $4.15 \times 10^{-5}\ \mathrm{m}^3/\mathrm{m}^2\ \mathrm{s}$ with respect to backwash efficiency and filtrate productivity.

A backwashing technique is not only operated using a flux of water as reported by Viero et al. [46]. In this study, the potential of using air as a medium for backwashing for a polyetherimide hollow fiber in an SMBR was reported. Even though more studies were conducted on other parameter effects, the authors concluded that an air backwash system is suitable for cake layer removal. However, any gel layer fouling cannot be avoided due to the hydrophilic nature of the membranes.

The application of a backwash system was found to be more effective than an aeration air flow system, however, this method was more effective when combined with an aeration fouling control strategy [47]. This finding also revealed that 98.5% of cleaning/regeneration was achieved using this combination technique, without any support of chemical cleaning agents or temperature enhancements.

An application of closed loop control systems in a backwash initiation is well adopted and was conducted by James et al. [48] in controlling a submerged membrane hybrid reactor. Irreversible fouling has been identified as a fouling that can be minimized by using a backwash technique. However, a periodic backwash cannot give satisfactory results as shown in Fig. 6. In this study, a TMP value was used as a feedback signal for the controller and the back flush frequency was controlled by using a linear increment of TMP. From the experiment, it was shown that the permeating flow of a variable back flush, using an automatic control, gave almost the same value with a fixed high-frequency back flush. However, from a performance point of view, an automatic control of a back flush has a superior result, because it saves 25% of the permeation required for back flushing, while maintaining the organic matter removal at 80–85%.

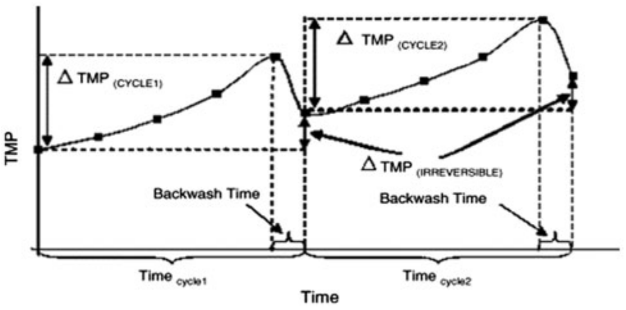

Fig. 6. Typical TMP profile of a membrane system operating with an intermittent periodic permeation production cycle and a periodic backwash cycle [49].

An improvement of a typical closed loop structure of a TMP control was reported by James et al. [49]. A series of experiments were conducted in order to observe the effect of a backwash duration on the fouling rate. A development of the control structure was also included where the backwash stabilizes lag in order to determine a stable operational system pressure at the start of each cycle. From the three series of experiments conducted in another paper by James et al. [49], it was found that the proposed approach improved the productivity and the energy consumption for an MBR system by a reduction of 40% of the backwash required in the filtration operation. In addition, the organic matter removal remained at a high level, between 80 and 85%, irrespective of the change of backwash duration. The application of an automatic closed loop control was also presented by Villarroel et al. [50] where the automatic backwash and the relaxation duration was considered as being the manipulated variables. In this work, the set point was pre-selected at an appropriate level, where in this case, the TMP was the set point selected by the controller's design. The result observed an increment of filtration length, cleaning efficiency, and reasoning productivity, and these were achieved by implementing an automatic cleaning procedure. A similar strategy was adopted by Vera et al. [51]. However, this work only covered a backwash frequency adjustment. The automatic control system was validated by a four-month experiment. The authors highlighted the importance of the TMP set point level selection, since any backwash efficiency would decrease at a higher TMP set point and chemical cleaning would be needed for any fouling removal.

Another closed loop backwash automatic control was developed by Vargas et al. [52] for a submerged membrane sequential bioreactor. The controller action was developed from systematic algorithms where the TMP and the flux was the feedback signal to the controller. The maximum current TMP and flux was compared with the maximum allowable TMP and the minimum allowable flux set point. The control variable was the backwash frequency. The backwash frequency would be increased if the TMP reached its maximum value, or the permeating level dropped to its minimum allowable permeation flux.

A model based control of a membrane filtration system is still new and is not mature. Alnaizy et al. [53] presented a simulation of neural network model predictive controls (NNMPC) to control the ratio of permeation-to-backwash time. The model was developed from another work by Alnaizy et al. [54], where the variation permeation-to-backwash ratio was tested and the permeation was measured for 15 d. The input–output neural network model was developed from the ratio and the permeation flux. The NNMPC decided that the control output was based on the permeating flux set point. However, the concept of this controller was only tested using a simulation model and where no real plant verification was made.

Chemical utilization in membrane cleaning is an important operational part in membrane filtration processes [55]. This type of cleaning can be done with a backwash operation. This chemical backwashing technique can be used to remove irreversible fouling. However, this technique can only be applied when normal backwashing is incapable of removing the fouling. Chemical cleaning must be executed at the right time and at the right frequency in order to prevent serious fouling and damage to the membrane itself [56,57]. Sodium hydroxide (NaOH), in particular, was found to be effective in chemical backwashing at low and high fluxes [58]. The achievement of NaOH backwashing was found to be at 50–69% in slowing the fouling rate, when compared with 40–50% when using a normal backwashing procedure from permeation flux. Sodium hypochlorite was used as the backwashing agent at both low and high fluxes [37]. The results from their experiments showed an improvement of flux recovery at a low level flux, which was more significant when compared to that at a higher flux. Another type of backwash using sodium hypochlorite was done by Wang et al. [59] for a submerged PVDF membrane, where they found that the chemical was effective in maintaining the TMP with a good flux recovery. However, this type of chemical when used, leads to severe fouling in any subsequent operation. This is due to the alteration in membrane properties caused by the chemical's effect. The right dosage of the sodium hypochlorite chemical is very important, because it will affect the micro-organism safety of the biological process [60]. The research reported that a chemical dosage of 1 mg-NaOCl/MLVSS was safe for the process. Short-term and long-term experiments have shown that optimal schedule chemical cleaning can improve a fouling rate's development [27]. A study of chemical backwashing for direct membrane filtration was done by Lateef et al. [61]. With a high membrane flux, it was found that 75% of the organic matter can be removed. The experiment conducted also showed that a proper selection of the chemical reagent as being an important factor in order to determine an efficient fouling removal and to enhance flux recovery. An interesting finding was reported by Wang et al. [62], where an excessively low and high usage of NaClO as a backwashing agent did not lead to a significant improvement of fouling rate development. However, the authors found that a low usage of NaClO can cause unfavorable effects of nutrient removal, but exposure to NaClO can improve the denitrification process in an SMBR. Both, water and chemicals were found to be effective in any flux enhancement as a result of an enlargement of the membrane pore. In the studies conducted by Lee et al. [63] for a high-flux flat sheet of polytetrafluoroethylene, an MBR backwash using the NaClO chemical showed that this technique could provide high flux, and was approximately twice that in a conventional filtration system, in both lab and pilot scale plants. Table 2 shows the various settings of a backwash operation.

4. Fouling control using a relaxation operation

Relaxation is defined as stopping the permeating process whilst continuing to scour the membrane with air bubbles [2]. Relaxation is a common method in membrane operations in submerged MBR systems for either hollow fiber or flat-sheet membranes [2] [66] and [67]. This technique is only applicable when removing reversible fouling. A longer relaxation time can help fouling removal and enhance the permeant flux [68]. However, a too long and a highly frequent relaxation would cause critical fouling due to the relatively high instantaneous flux [42]. An optimization of the relaxation time interval is seen to be crucial for this technique when dealing with fouling removal. Several works on the optimization of relaxation techniques have been developed in order to limit fouling development. In the works of Wu et al. [42], three sets for three runs of relaxation intervals were used in order to observe the optimum relaxation interval when compared with that of a continuous flux. The authors observed that from the three runs, the effect of an instantaneous flux was more dominant than the relaxation interval. However, from the three relaxation settings, the longest interval (440 s) exhibited a more effective fouling control. The relaxation period was not that much affected by fouling when compared with the interval duration. The effect of relaxation is clearly shown in Fig. 7.

The relaxation operation influences the efficiency for an anaerobic submerged MBR for palm oil mill effluent as studied by Annop et al. [69]. In this study, four runs were used to obtain an optimized relaxation interval. The permeation duration for each run was set to 240, 480, 720, and 960 s, while maintaining a

Table 2
Backwash setting survey

Refs.	Plant scale	Membrane type	Backwash to permeating ratio (minutes)	Permeate flux	Backwash flux
Aidan et al. [40]	Lab	Flat sheet	2:10	180–140 L/m^2 day	–
Wu et al. [42]	Lab	Hollow fiber	0.66:8	24.5 L/m^2 h	30 L/m^2 h
Jiang et al. [44]	Pilot	Hollow fiber	0.75:10	25 L/m^2 h	–
Hwang et al. [45]	Lab	Ceramic	2:30	–	4.15 × 10^{-5} m^3/m^2
Qaisrani et al. [47]	Lab	Flat sheet	0.5:8	–	–
Bouhabila et al. [28]	Pilot	Hollow fiber	0.25:15	13 L/m^2 h	–
James et al. [49]	Lab	Hollow fiber	0.25:15	40–48 L/m^2 h	96 L/m^2 h
Zhou et al. [58]	Lab	Hollow fiber	18:162	6.5–13 L/m^2 h	8.33 L/m^2 h
Ye et al. [64]	Lab	Hollow fiber	0.5:60	73 L/m^2 h	109.5 L/m^2 h
Raffin et al. [65]	Pilot	Hollow fiber	1.25:15	30–50 L/m^2 h	–
Zsirai et al. [37]	Full	Hollow fiber	0.5–1: 6–12	10–25 L/m^2 h	16–38 L/m^2 h

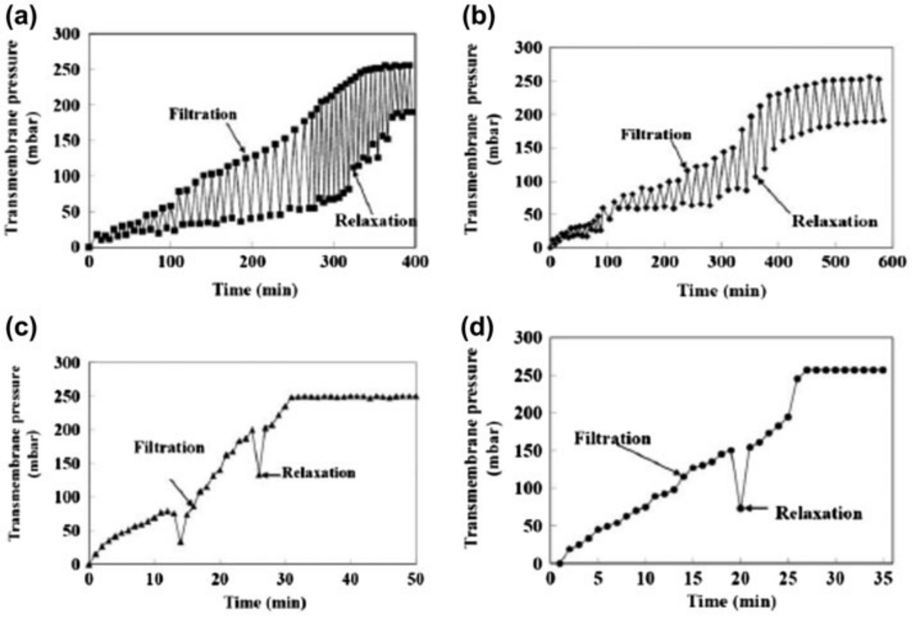

Fig. 7. Variations of TMP under different intermittent permeating filtration modes: (a) 240 s filtration/30 s relaxation, (b) 480 s filtration/30 s relaxation, (c) 720 s filtration/30 s relaxation, and (d) 960 s filtration/30 s relaxation [69].

relaxation period of 30 s for all four runs. From the four runs, the second run showed the best setting, with the fouling reaching its maximum. The longest permeation (of 960 s) showed a rapid fouling which took 30 min to reach its maximum. Too high a frequency of relaxation was not determined by a low fouling development, and thus, an optimal relaxation period was needed to be obtained, prior to the plant's operation.

A study of the effectiveness of a relaxation for reversible and irreversible fouling was conducted by Zsirai et al. [37]. Rahimi et al. [34] compared the relaxation effectiveness with a backwash technique. From the literature, it was concluded that a relaxation technique was comparable with a backwash technique in terms of a TMP increment. However, for irreversible fouling, a relaxation technique was very poor when trying to maintain the permeability.

A review by Wang et al. [38] found that several researchers had combined a relaxation technique with a backwash technique, in order to obtain a more effective cleaning result for membrane filtration. The

Table 3
Relaxation settings from various researches

Refs.	Plant size	Membrane type	Filtration	Relaxation	Flux
Wu et al. [42]	Lab	Hollow fiber	440 s	20 s	21
Zsirai et al. [37]	Full	Hollow fiber	7–12 min	40–3 min	10.3–28
Annop et al. [69]	Lab	Hollow fiber	480 s	30 s	20
Hong et al. [72]	Lab	Hollow fiber	145 min	15 min	–
Oh et al. [73]	Pilot	Hollow fiber	9 min	1 min	17.5–25.7
Ferrero et al. [24]	Pilot	Flat sheet	9 min	1 min	–
Zuo et al. [68]	Lab	Rotating	8	2	47.5
Dalmau et al. [74]	Full	Flat sheet	9	1	15–25 L/m^2 h
Guglielmi et al. [27]	Pilot	Flat sheet	9	1	10–15 L/m^2 h
Guglielmi et al. [75]	Pilot	Hollow fiber	540 s	60 s	10–15 L/m^2 h

authors also highlighted that it was important to consider the net permeation flux, in order to optimize the relaxation period, due to the lost permeation during the relaxation period. There are two equations which ought to be utilized in a relaxation time consideration, which are the effective flux and the effective permeability.

$$J_{\text{eff}} = \frac{(J_{\text{f}} \times t_{\text{f}} - J_{\text{b}} \times t_{\text{b}})}{(t_{\text{f}} + t_{\text{r}} + t_{\text{b}})} \tag{2}$$

$$K_{\text{eff}} = \frac{J_{\text{eff}}}{\text{TMP}} \tag{3}$$

Eq. (2) presents the effective flux J_{eff} and Eq. (3) presents the effective permeability K_{eff} Where J_{f} is the filtration flux, J_{b} is the backwash flux, and t_{f}, t_{b}, and t_{r} are the filtration time, the backwash time, and the relaxation time, respectively.

The simulation work by Ludwig et al. [70] showed that the optimization technique used genetic algorithms for the optimal filtration-to-relaxation ratios. This work used an ASM1 model by Henze et al. [71], integrated with a membrane filtration system using GPS-X software. From the simulation results, the authors reported that 49 min of filtration and 10 min of relaxation was the most optimum ratio when compared to the standard nine minutes filter and the one minute of relaxation time that was implemented in the system. In addition to that, an optimum filtration and relaxation may reduce the costs in terms of cleaning and maintenance. Table 3 presents the relaxation settings from the various previous researchers.

5. Conclusion

Aeration is the most effective fouling control in submerged filtration systems. However, an aeration control must consider several important factors which include cost, effectiveness, and optimization. An excessive amount of aeration is found to be ineffective when controlling fouling, as it exceeds a critical value, and although there is no further effect on fouling, the aeration cost is increased. Further effects on high aeration can also cause breakages on the flock that will result in rapid irreversible fouling and a low quality of the nitrification process. Low aeration is also not suitable for membrane filtration, since the scouring sheer intensity is not high enough to remove the cake resistance fouling. A closed loop application of an aeration control or an air scouring control is becoming more important in a submerged MBR filtration, since the effectiveness of this technique proves that it can reduce aeration costs. However, this control technique is still much dependant on knowledge-based algorithms, and a prior knowledge of the dynamic filtration characteristics in developing the algorithms is required. Several feedback parameters have shown their potential to be utilized as fouling feedback indicators, such as fouling sensors, TMP, MLSS, and permeating fluxes.

A backwash technique is one of the available methods that can be used to slow down irreversible fouling. An optimal duration and intensity are the key factors in order to prevent rapid irreversible fouling and a fast increment of TMP. At the moment, the technique of an exhausting experiment is more popular in order to obtain the optimal backwash operation. Several of the works on automatic backwash scheduling have shown good results for an improvement of a membrane filtration process. A variable automatic controlled backwash can also reduce the backwash energy as the cycles for backwash are reduced. A chemical cleaning backwash system seems to be a very important operation in SMBR. The proper selection of chemicals is very important, not only to ensure the filtration enhancement, but it must also consider the biological process in the membrane reactor itself, so that nitrification and denitrification can occur effectively. However, a low and a high critical point must be obtained, in order to get a constrained range of the control output, so that it can obtain optimal scheduling. The works on a backwash scheduling model's prediction also has the potential to develop into a model-based control for backwash scheduling.

Finally, this review also covers a relaxation technique for membrane filtration systems. A relaxation technique is less effective on fouling when compared with a backwash technique. However, relaxation is effective in controlling fouling development, especially when combined with suitable aeration intensity. A good combination can effectively aid in reversible fouling, as the phase of relaxation makes the membrane undergo less stress, and the fouling can effectively be removed under this condition. Identical to the backwash technique, a relaxation method also has a lower and an upper point of critical value, as a high frequency of relaxation cannot guarantee a slow development of fouling. Other advantages of relaxation are that this technique will result in less energy being used, since no backwash pump is needed. A relaxation technique is also found to be better in terms of permeation loss caused by the permeation being used as a medium for a backwash operation.

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