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# Membrane bioreactor technology for treatment of nitrogen rich wastewaters — A critical review

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**ABSTRACT**

Membrane bioreactor (MBR) technology combines the activated sludge process and membrane filtration in a single step, where the separation of activated sludge and effluent is achieved with the help of the membranes. MBR permits good control of biological activity and high organic loading rates resulting in high quality effluent and small plant size. This paper reviews the potential applications of the MBR technology for the removal of nitrogen from effluents. The study reveals the prospects of choosing the right configuration of MBR (aerobic, anoxic/ anaerobic, completely anaerobic, integrated anaerobic/aerobic) for treatment of nitrogen rich wastewaters.

*Keywords:* Membrane bioreactor (MBR); Aerobic MBR; Anaerobic MBR; Nitrogen removal; Membrane fouling

## 1. Introduction

Ammoniacal nitrogen rich wastewaters are discharged into surface water bodies from various sources such as starch production (800–1100 mg/L), municipal solid waste landfills (500–3000 mg/L), domestic wastewater (100 mg/L), swine farms (115–175 mg/L), sludge liquor (100–2000 mg/L), yeast production (180–450 mg/L), and fertilizer manufacture (500–1000 mg/L) result in eutrophication and depletion of oxygen content in aquatic ecosystem [1–5]. About 1.0 mg of ammoniacal nitrogen exerts an oxygen demand of 4.6 mg when converted to nitrate nitrogen. Emissions of nitrous oxide to atmosphere during oxidation of ammonia, and toxicity to aquatic invertebrate and vertebrate species are the other effects of discharge of excess ammonia into the environment. For example the tolerance limit for salomonid fish is 0.5 mg $NH_3$-N/L, and $LC_{50}$ (96 h) for tiger prawn and Australian crayfish is 14 and 26 mg $NO_2^-$/L respectively [6–9]. Nitrite nitrogen let out into water bodies without treatment may cause methaemoglobinemia and gastric cancer among human populations [9].

Biological treatment methods involving nitrification and denitrification carried out by autotrophic nitrifiers (aerobic) and denitrifiers (anaerobic) are conventionally used for removal of nitrogen from wastewaters to meet the regulatory discharge limits (ammoniacal nitrogen – 50 mg/L; nitrate – 10 mg/L for inland surface waters) [1,2,10]. This requires more number of treatment units that results in high production of sludge (1 kg of VSS/kgN) and lower removal efficiency (75% of Amm–N) [9]. Advanced biological treatment process such as membrane bioreactor (MBR) has the potential to overcome the shortcomings of conventional treatment techniques.

MBR combines the merits of the activated sludge process (ASP) and membrane filtration in one treatment step, where the membranes act as a solid-liquid separator [11,12]. The various benefits of MBR include large scale

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removal of organic load, toxic components and inorganic anions like nitrate, fluoride, arsenic species etc. [13–16]. The other advantages of the MBR are good retention of biological activity (mixed liquor suspended solids (MLSS) – 12–15 g/L), consistent quality of effluent free of bacteria and pathogens (coliform removal = 5–8 log), low sensitivity to contaminant peaks, higher rate of nitrification and denitrification [17], operation flexibility and better process reliability, low sludge production (0.20 kg SS/ kg COD) and higher organic loading rates (upto 20 kg COD/ $m^3$/d) [18–21].

Keeping in mind the above considerations, this paper attempts to critically evaluate the potential of aerobic and anaerobic MBRs for the treatment of nitrogen rich wastewaters. The different schemes of the MBR proposed for the nitrogen removal process reported in the literature are analyzed for various operational parameters which determine the performance efficiency of MBR. The paper has also identified the research and development needs in the use of MBR for the treatment of nitrogen-rich wastewaters.

## 2. Types of membrane bioreactor

External and internal type of MBR configurations are widely in vogue [22]. In the external MBR (also known as the recirculated type) membranes are present external to the reactor. In the internal MBR (also known as integrated or submerged type) membranes are present internal to the reactor. In the external type, pressure is created by high cross flow velocity along the membranes, whereas in the submerged type, the impetus across the membrane is realized by the bioreactor pressure [23,24].

The cross flow velocity of the effluent across membrane serves as the principle mechanism to disrupt cake formation on the membrane. The mixed liquor is kept in suspension using diffusers or baffles as employed by Kimura et al. [25,26]. It is reported in their studies that baffles created alternative aerobic/anoxic conditions favorable for nitrogen removal (70%) in municipal wastewater. In another study by Hai et al. [28] both baffles and diffusers are used in treating synthetic textile effluent using submerged MBR. The submerged MBRs are most commonly used owing to its ease of operation and high performance efficiency [25,27,28].

### 2.1. Aerobic MBR

Aerobic MBRs have an external aerator that provides the required agitation by vigorous bubbling of oxygen across membrane surface to prevent cake formation, to maintain the solids in suspension, and to supply dissolved oxygen to the microorganisms. In the submerged aerobic MBRs, aeration is also used for membrane scouring [29]. Aerobic MBRs are usually applied in full scale wastewater treatment. Application of aerobic process is meant for wastewater with low organic loading rate due to oxygen transfer limitation and high bacterial sludge production [30]. Aerobic MBRs may be adopted for treatment of landfill leachate [31], and removal of contaminants like acrylonitrile, butadiene and styrene (ABS) from industrial wastewater [32]. Aerobic MBRs are usually applied in full scale applications of wastewater treatment.

### 2.2. Anaerobic MBR

The anaerobic type MBR is generally adopted to favor nutrients and organic matter removal, when intense aeration poses difficulty in realizing efficiency. An anaerobic MBR (An MBR), operated without oxygen, offers several widely acknowledged advantages over conventional aerobic processes such as high loading rate, less energy requirement, less production of biomass and production of valuable biogas [22,30,33] which were used for treating domestic wastewater [27,30,34,35], nitrate contaminated streams [25,36,37] and high strength industrial effluents [22,38]. These advantages are offset by slow growth rates of the methanogenic bacteria and microbial complexity of the systems due to longer retention time. The comparison of experimental parameters between aerobic and anaerobic MBRs is presented in Table 1.

### 2.3. Membranes in MBR

Membranes used for MBR applications vary with its material of construction (organic such as polyethylene, polyamide, polyethersulfone, polysulfone, polyolefin, polyvinylidene fluoride, etc.) and inorganic such as metallic and ceramic, kind of module (tubular, plate and frame, flat sheet, rotary disk, hollow fiber), filtration surface (inner skin or outer skin) and module status (static or dynamic membrane) [14,23,25,28,30,31,35,40–43]. The pore size of the membranes ranges from 0.01 to 0.4 μm depending on the type of membrane (microfiltration, ultrafiltration and nanofiltration membranes) used.

Table 1
Comparison of aerobic and anaerobic MBR performance [35]

| Operational parameters | Aerobic MBR range | Anaerobic MBR range |
|---|---|---|
| MLSS, g/L | 12–15 | 8–50 |
| Coliform removal, log | 5–8 | — |
| Sludge production, kg SS/kg COD | 0.20 | — |
| Organic loading rates, kg COD/$m^3$/d | up to 20 | 2–22 |
| HRT, d | 1–5 | 0.5–15 |
| SRT, d | 40–75 | 30–160 |
| Solids yield, g VSS/g COD | — | 0.04–0.12 |

It has been reported that the major factors affecting the performance of MBR were microbial activity, operational pressure, temperature, sludge retention time (SRT), hydraulic retention time (HRT), reactor design and membrane location [8,22,44]. Besides these, membrane flux, mixed liquor suspended solids (MLSS), sludge age, pore size of membrane, materials used for membrane preparation and hydrodynamics of the membrane separation have also been known to significantly influence the performance of MBR systems [27,44].

## 3. MBR for nitrogen removal in wastewaters

### 3.1. Lab scale applications

Laboratory based studies on biological nitrogen removal has been accomplished using various combinations of MBR involving anaerobic, anoxic, and oxic manipulations as detailed in this section. Treatment of domestic synthetic wastewater in lab scale by Chu et al. [45] has achieved a simultaneous removal of organic load and total nitrogen was 93% and 77% respectively. Likewise Canziani et al. [31] has achieved a biological nitrogen removal from old landfill leachate by 0.5–3 g/L $NH_3$-N concentration upon partial nitrification to nitrite in a pure oxygen membrane bioreactor (PO–MBR) and by subsequent denitrification in a moving-bed biofilm reactor (MBBR) with SRT higher than 45 days. Visvanathan et al. [46] carried out treatment of aquaculture wastewater for the removal of nitrate using aerobic MBR in 2 combinations of aeration–denitrification system (ADS) and denitrification–aeration system (DAS). Around 91% removal of nitrogen was achieved by DAS with HRT of 3 days and denitrification rate at 363.7 mg/L/d.

### 3.1.1. Single reactor type MBR with intermittent aeration type

Seo et al. [47] have carried out 2-stage intermittent aeration using submerged MBR. This system involved alternating the aerobic/oxic and anoxic conditions in a single reactor MBR system, with periodic supply of oxygen in decided intervals and duration as depicted in Fig. 1 [42]. The total nitrogen removal efficiency was 92% along with 98% and 96% removal of BOD and COD respectively. This high performance was optimized at 60 min intermittent aeration cycle.

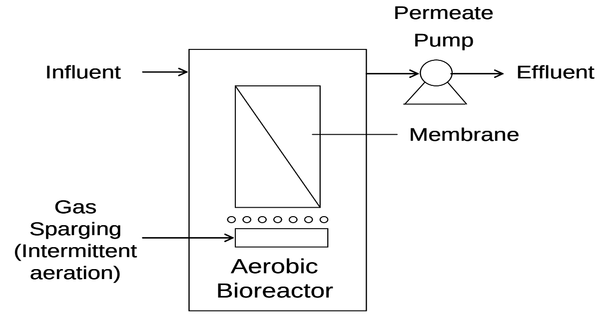


Fig. 1. Schematic of a single reactor type MBR with intermittent aeration type.

Similarly in the studies carried out by Ujang et al. [48], for an influent COD of 650 mg/L and nitrogen of 30 mg/L, attained about 98% of organic load removal and 96% of nitrogen removal. This was achieved with periodic aeration and non aeration cycle optimized at 120/120 min. But due to this cyclic oxygen supply strategy, the filtration operation was limited in oxic cycle alone because of preventing membrane fouling. The time cycle of aeration and non aeration was mainly adopted for nitrogen removal along with simultaneous reduction in carbon in the submerged MBR system [15].

### 3.1.2. Modified Luzack–Ettinger (MLE) type MBR

This is a continuous aeration and filtration system with an exclusive anoxic tank for denitrification with membrane coupled anoxic/oxic process [15,42]. The recycling of mixed liquor from membrane area to anoxic tank occurs continuously as indicated in Fig. 2. In this system, denitrification efficiency is reduced in the anoxic zone, due to the entry of high dissolved oxygen (DO) concentration (2–6 mg/L of DO) which is normally found in the recycle stream [49]. This issue could be addressed by splitting the recirculation of mixed liquor sludge to aerobic tank and then with a control valve the remaining sludge be sent to the anoxic tank.

The benefit of completely decoupling the solids recycling requirements from the denitrification requirements is provided by dual recycle configuration or by making

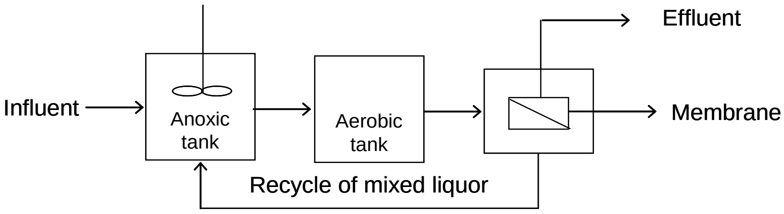


Fig. 2. Schematic of modified Luzack–Ettinger (MLE) type MBR [49].

use of deaeration zone upstream of the anoxic zone [49]. Although, the improvement in nitrogen removal is better than single reactor type, it could still be inadequate to meet the standards because the nitrogen removal efficiency is found to be 67.4% in the MLE type MBR process [15].

### *3.1.3. Sequencing anoxic/anaerobic type MBR (SAM)*

The innovative SAM process involves sequencing the anaerobic and anoxic condition in a single tank by switching on and off the recirculation of mixed liquor to induce anoxic condition from the ensuing continuous aerated MBR as depicted in Fig. 3. Ahn et al. [15] have performed nutrient removal studies for household wastewater of 30 and 37 mg/L of ammoniacal nitrogen and total nitrogen respectively. The HRT of this type of MBR process has been reported to be is nearly 2.3 times longer shorter than that of MLE type MBR, while MLSS was maintained at 10–11 g/L. In this study the submerged membrane bearing the aerobic zone is continuously aerated for nitrification to prevent fouling. Management of SAM conditions are carried out by sporadic recycle of mixed liquor from aerobic zone to the anoxic/anaerobic sequencing zone directly to alternate the anoxic conditions for denitrification and anaerobic conditions for phosphorous release. The entire operation is maintained at a flux of 10 L/m$^2$/h (30 L/d).

The performance of the lab scale SAM process yielded 60% total nitrogen, 96% (mean of 10 mg/L COD in effluent) removal with an SRT (sludge retention time) of 70 days. The degree of nitrogen removal of SAM process is possible owing to an enhanced phosphorous release and phosphorous uptake during anaerobic and anoxic phase respectively. Due to excess phosphorous uptake in aerobic zone, it resulted in denitrification simultaneously. The formation of autotrophic bacteria in aerobic zone with absolute denitrification was because of using up the biodegradable COD in the anoxic/anaerobic zone for denitrification [42]. Though the nitrogen removal by SAM is inferior to MLE process, it could be improved by modifying the rate of internal recycle and extent of anoxic phase, because the degree of denitrification in anoxic/anaerobic zone determines the efficacy of total nitrogen removal.

This could be considered as a flexible option for nutrient removal than intermittent aeration method, as organic substrate in the influent is effectively used up for nitrogen removal. But since the nitrogen removal is less than MLE process (60%), so optimization of the MBR process garnered attention.

### *3.1.4. Alternate anoxic and anaerobic type MBR (AAAM)*

The working principle of this improved nutrient removal system included alternating the anaerobic and anoxic zone between 2 separate bioreactors from a continuously aerated MBR [42] unit as shown in Fig. 4. This type of MBR fulfills the demands for anoxic condition for denitrification and anaerobic condition for phosphorous release. 93% and 67% of organic and nitrogen removal were achieved, with an influent of 300 mg/L of COD and 30 mg/L Amm–N.

In the study carried out by Yuan et al. [42], the anoxic condition is created for 1 h due to the introduction of dissolved oxygen and nitrate in mixed liquor from the aerobic zone. Whilst anaerobic condition is induced for 1h in the absence of recycling, in 2 single tanks alternately. Fatone et al. [50] have demonstrated the treatment of domestic wastewater of C/N ~ 5 by altering aerobic and anoxic cycles in continuous study for effective nitrogen removal (69%). Nitrogen removal is favored not only by denitrification, but also by usage of nitrogen by microbes for cell growth. The advantage of this mode is the complete utilization of organics substrate occurring in the effluent, by the nitrifiers and denitrifiers due to the favorable conditions.

### *3.1.5. Complete anaerobic type MBR*

Treatment of domestic wastewater of composition 640 mg/L of COD and 60 mg/L of ammoniacal nitrogen was studied by Grundestam and Hellstrom [16] using an external anaerobic membrane bioreactor module as shown in Fig. 5. Sludge from the bioreactor as well as permeate from the MBR unit is recycled back. The 1 L reactor is

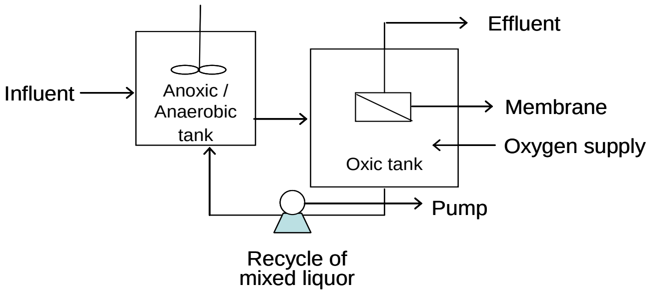


Fig. 3. Schematic of sequence anoxic/anaerobic MBR (SAM) [15].

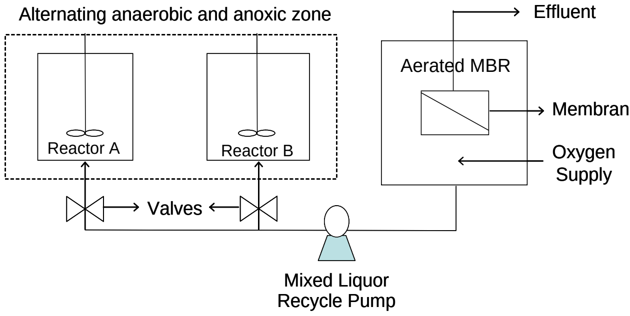


Fig. 4. Schematic of alternate anoxic and anaerobic type MBR (AAAM) [42].

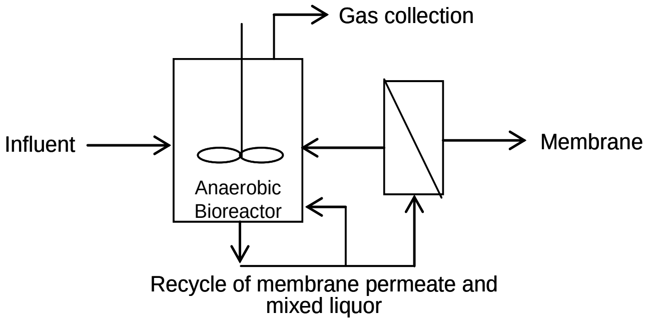


Fig. 5. Schematic of complete anaerobic type MBR.

operated with HRT of 0.6 d. The OLR is maintained at 0.8 kg COD/d. Reduction of nitrogen and organic matter using An MBR is 9% and 92% respectively along with stable methane gas production (average 0.7 $m^3$/wk). The biogas generated in An MBR may be used for sparging purposes [22]. Akin to this recycling pattern, the AnMBR system adopted by Beaubien et al. [38] have accommodated permeates recycling port, to allow constant HRT (1 d) of the process. The removal of COD was >95% for OLR of 0.8–0.9 kg COD/kg VSS d. The performance of the system to remove COD reduced to 65% when the rate of loading was increased to 1.2 kg COD/kg VSS d, while the nutrient removal rates are not reported. The issue of lack of stirring was interestingly addressed by Grundestam and Hellstrom [16]. They had adopted a jet flow inlet and permeate recycling, which bolstered the medium homogenization. The biogas production was 30 L/d with a loading rate of 2 g COD/L/d and rate of methane generation was directly proportional to rate of organic loading. The methane content in biogas was about 0.27 L CH4-g-COD–1.

Similarly Saddoud et al. [34] had reported removal of TSS, COD and BOD to be 100, 88 and 90% respectively. In this investigation, municipal wastewater had been treated using an anaerobic cross flow ultrafiltration membrane bioreactor with OLR of 0.23–2 g COD/L/d and MLVSS of 4.3–4.9 g/L.

Anaerobic MBR studies carried out by Grundestam and Hellstrom [16], Saddoud et al. [34] called for post treatment options like reverse osmosis to favor better removal efficiencies.

### *3.1.6. Biological nutrient removal by various recirculation configurations of MBR*

In a study for nitrogen removal on municipal wastewater by Ersu et al. [51], besides the internal recirculations of mixed liquor, MBR filtered permeate was also used, as depicted in Fig. 6. The variations in recycling the mixed liquor and/or permeate into different locations of anoxic and/or anaerobic chambers was performed to enable improved denitrification furthering the efficiency of the nutrient removal process [42,51].

Table 2
Summary of performance efficiency of different MBR configurations

| MBR configurations | COD removal (%) | Nitrogen removal (%) | Ref. |
|---|---|---|---|
| Single reactor with intermittent aeration | 96 | 92 | [47] |
| | 98 | 96 | [48] |
| MLE | — | 67 | [15] |
| SAM | 90 | 60 | [15] |
| AAAM | 93 | 67 | [42] |
| Complete anaerobic | 92 | 9 | [16] |
| | >95 | — | [38] |

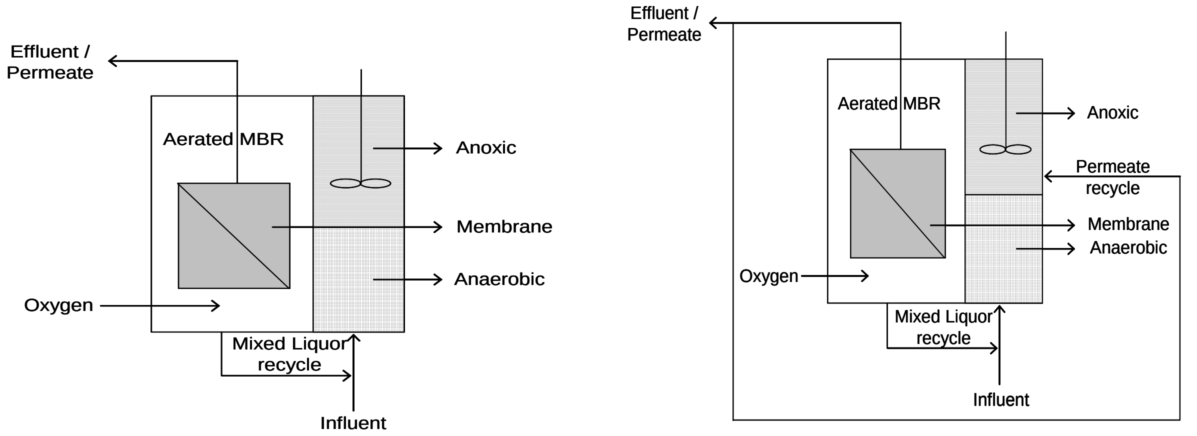
Effective removal of nutrients from nitrate-contaminated wastewaters has also been achieved by Delgado et al. [41], Yuan et al. [42], Ersu et al. [51] and Abegglen et al. [52]. Recirculation of mixed liquor and permeate is adopted to raise biological nutrient removal (as high as 92%) [51]. High rate of recycling favored redistribution of the sludge inventory [49]. Biological nutrient removal (BNR) studies have also been investigated by Ramphao et al. [53], McAdam and Judd [54], Bracklow et al. [55]. The abridgment of the nitrogen removal performance of MBR for domestic wastewater is highlighted in Table 2.

From the table it is understood that both organic load and nitrogen removal was highest when intermittent aeration was operated in a single reactor MBR. The low rate of performance may be attributed to fouling of the membrane, due to interaction between the membranes and the components of activated sludge liquor [45,50].

### *3.2. Pilot scale applications*

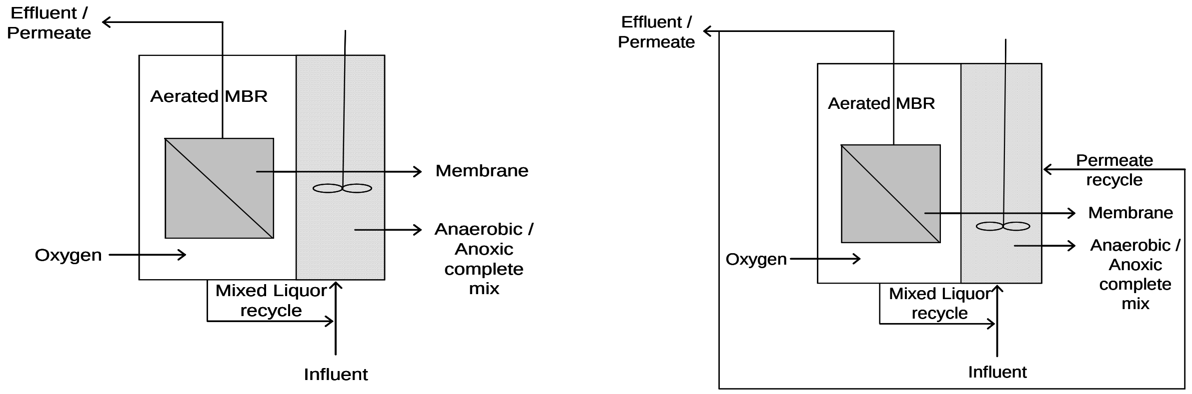
Domestic wastewater reclamation project has been undertaken as a pilot study in 2 MBR units (20 and 10 $m^3$/d capacity) by Chen et al [56] in Bali, Taiwan. >90% removal of $NH_3$-N and >75% removal of COD is achieved and the reclaimed water is used for irrigation. Likewise, Abegglen et al. [52] carried out an on-site treatment of domestic wastewater for a 4-member house, with a combination of the 1st reactor (primary clarifier) followed by the 2nd reactor (MBR). Recycling of activated sludge facilitated during the operation of anaerobic/ anoxic condition favoured nitrogen and phosphorous removal of 90% and 70% respectively, as compared to 50 and 25% removal during operation as primary clarifier.

Cho et al. [57] studied operations of a SAM pilot plant for nutrient removal from the municipal wastewater. The system has been reported to be composed of sequencing anoxic/anaerobic reactor (SAAR) and an aerated reactor (AR) containing the microfiltration membrane, with similar intermittent recycling of mixed liquor from AR to SAAR as that of Ahn et al. [15]. In the SAAR system, the anoxic environment is maintained for 3 h in a cycle of



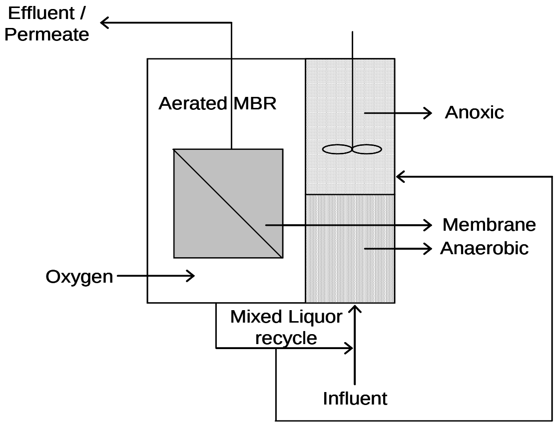
(i) Mixed Liquor recycled to anaerobic zone of Bioreactor

(ii) Mixed Liquor and Permeate recycled to anaerobic zone and anoxic zone of Bioreactor



(iii) Mixed Liquor recycled to anaerobic / Anoxic zone complete mix of Bioreactor

(iv) Mixed Liquor and Permeate recycled to Anaerobic / Anoxic complete mix zone of Bioreactor



(v) Mixed liquor recycled to anaerobic and anoxic zone of Bioreactor

Fig. 6. Biological nutrient removal using various recirculation configurations of MBR [51].

4 h with internal recycle, while the anaerobic period is for 1 h in the same 4 h, with no recycle. The water quality of influent nitrogen and organic load is about 25 mg/L and 150 mg/L respectively, and the effluent is around 8 and 7 mg/L respectively. In SAAR unit, during recycling, nitrate accumulation and denitrification has occurred in the anoxic zone, while nitrification has occurred in AR unit.

### *3.3. Full scale applications*

Kocadagistan and Topcu [35] performed treatment of municipal wastewater in Erzurum city, Turkey using AnMBR integrated with cross-flow microfiltration unit (CFMF). About 98.1% removal of organic load and 99% removal of suspended solids were attained. While Galil and Levinsky [58] have evaluated the treatment of industrial wastewaters from paper mill, food production and petrochemical operations by making use of aerobic MBR (hollow fiber type). While treating the effluent of paper mill industry, COD reduced from 960 to 130 mg/L with 86% removal efficiency and BOD reduced from 363 to 7 mg/L with removal of 98%. Substantial reduction of TKN (90%) and ammonia (90%) was also observed. The MLVSS was maintained at 11 g/L for the entire period of operation of 4 months. Whilst treating the effluent from food production unit a high percentage of removal of BOD (99%) was noted while a TOC reduction of 59% and 60% was observed for the ballast and bilge wastewaters respectively.

Whilst Kim et al. [43] carried out the treatment of swine wastewater and has been able to achieve a removal efficiency 99.88% of suspended sludge, 99.9% volatile suspended sludge, 99.97% COD, 99.95% TN, 99.94% $NH_3$-N, and 99.92% $NO_3$-N in the final effluent.

## 4. Control of membrane fouling — the challenge

Membrane fouling has deemed to be a limitation, crippling the wide usage of MBR, because it dampens productivity, mainly causing problems in membrane filtration, reduces membrane permeability and the treated water output flow and lessens the life of the membrane [44,50,57]. Fouling is due to scaling (clumping of low soluble inorganic species), organic fouling (adsorption of organic materials) and biofouling (attachment and development of microbes on membrane surface). Biofouling gains importance owing to increased usage of organic membranes [59]. Likewise membrane fouling in anaerobic MBRs is composite fouling that includes biofouling, organic and inorganic fouling [22].

Generally fouling or cake formation is dependent on the nature of feed to the membrane, characteristic properties of membrane and sludge formed, design and operation of reactor and environmental conditions [33,60]. Fig. 7 depicts the different stages of membrane fouling that involved an initial short tem rise in TMP (transmembrane pressure) due to conditioning, long-term rise in TMP and a sudden rise in TMP, called as TMP jump, with a sharp increase in TMP with respect to time [60].

Factors causing fouling in MBR are identified as EPS (extracellular polymeric substance) and SMP (soluble

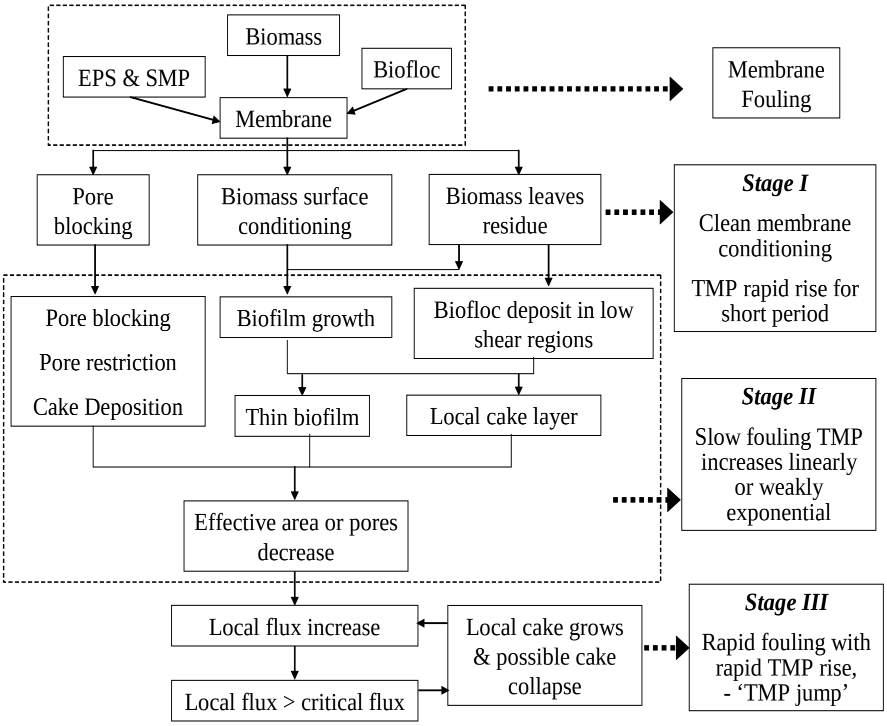


Fig. 7. MBR fouling mechanisms — 3 stages of fouling [60].

microbial products) [61,62]. EPS is of biological origin that takes part in the formation of microbial aggregates, and consists of insoluble materials (sheaths, capsular polymers, condensed gel, loosely bound polymers, and attached organic material). SMPs are soluble cellular components or soluble EPS (solute macromolecules, colloids and slimes).

Jang et al. [62] conducted batch filtration using sludge taken from pilot MBR that was used for treating domestic wastewater. They have compared the characteristics of membrane biofouling with regard to nitrification and denitrification. It has been reported that EPS concentration and relative hydrophobicity reduced after denitrification and resulted in floc deterioration. However, SMP concentration increased after denitrification and resulted in membrane pore blocking. Fouling became worse after denitrification owing to cake layer resistance and pore blocking resistance.

Fouling could be managed by regular membrane cleaning (using chemicals) or backwashing (with permeate or air or both) and optimizing the operational parameters to slack down the rate of fouling such as low pressure, high turbulence, intermittent filtration [44,50]. Aeration in membrane module had been attempted to avoid fouling [41]. Rezania et al. [36] overcame the issue of membrane fouling in An MBRs by $N_2$ gas scouring or cake formation could also be prevented by recirculation of biogas produced. Choi et al. [23] stated that short HRT and high flux condition accelerated membrane fouling; therefore by addition of more membrane modules to meet high HRT without increasing the membrane flux, fouling was controlled.

In the studies carried out by Grundestam and Hellstrom [16], membrane cleaning has been carried out using warm tap water, detergent and NaOH or HCl for 0.5 h. Detergent and alkali addition favors removal of organic matter, and acid for removal of fouling due to chemical precipitation.

Yuan et al. [42] has carried out intermittent suction and sub-critical flux (10 L/h) operation to alleviate membrane fouling, while Ahn et al. [15] performed intermittent operation of membrane with 8 min suction and 2 min rest and air scouring to minimize fouling. Fouling due to elevated MLSS concentrations (>15–18 g/L) could be minimized by recycling of the sludge inventory [49]. Membrane cleaning by both physical and chemical methods in turn has been performed by Li et al. [63]. The membrane modules are cleaned with tap water and then with 5% NaOCl and 5% HCl solution to remove foulants adsorbed on the membrane surface or within the pores. The contact times in NaOCl and HCl is 15–20 min. The chemical cleaning could remove most of foulants on or within the membrane with the recovery of 100%. While Chu et al. [45] adopted periodic 10-min backwashing and intermittent membrane effluent to reduce membrane fouling. 0.3% NaOCl has been selected as the membrane-cleaning agent. Rate of fouling could also be mitigated by controlling production of EPS (extracellular polymer substance), regulating air sparging and module design issues [64,65].

## 5. Future research

Though till date so many ways to mitigate the issue of fouling and improve the performance of nitrogen removal using MBR technology had been carried out, still lot more needs to be addressed. Like for instance, few full scale operations of MBR especially on nitrogen rich industrial wastewaters had been reported. Hence more studies on pilot scale operation are required in order to apply the same on the field scale.

Similarly elaborate works on biological effects on membrane fouling due to nitrogen rich wastewaters on MLE, SAM, AAAM, and complete anaerobic MBR processes, improvement of the nitrogen removal systems by increasing the duration of anoxic phase and flow rate of internal recycle, modifying the MLE, SAM, AAAM processes by stabilizing the operation mode with respect to different influent quality can be considered for forthcoming investigations. Influences of EPS and SMP in membrane fouling during the MLE, SAM, AAAM and complete anaerobic MBR units and optimizing the operational conditions to favor both nitrogen and organic removal by the MBR processes are the challenges that needs to be addressed in the future.

## 6. Conclusions

Contemporary research studies has pointed out that certain configurations of MBRs could operate better in removing and breaking down the organic components and nutrients in nitrogen rich wastewaters. The complete retention of the microbes along with recirculation of sludge had lead to acclimatization of biomass and improved kinetics of the reaction. The prospect of developing more efficient membranes by combining the removal of organic matter and nutrients in one treatment system is certain to invigorate future research and development and find wider applications of MBR in wastewater treatment.

## References

[1] N.D. Berge, D.R. Reinhart and T.G. Townsend, The fate of nitrogen in bioreactor landfills, Crit. Rev. Environ. Sci. Technol., 35 (2005) 365–399.

[2] J.M. Alvarez, Operation and model description of advanced biological removal treatments of highly ammonium loaded wastewaters, Doctoral thesis, University of Barcelona, Spain, 2007.

[3] J. Ridenoure, Optimization of nitrogen removal from anaerobically-pretreated swine wastewater (APTSW) in intermittent aeration reactors, MSc thesis, North Carolina State University, 2004.

[4] K.A. Third, Oxygen management for optimization of nitrogen removal in sequencing batch reactor, Doctoral thesis, Murdoch University, Western Australia, 2003.

[5] I. Schmidt, O. Sliekers, M. Schmid, E. Bock, J. Fuerst, J.G. Kuenen, M.S.M. Jetten and M. Strous, New concepts of microbial treatment processes for the nitrogen removal in wastewater, FEMS Microbiol. Rev., 27 (2003) 481–492.

[6] C.A.L. Chernicharo, Post-treatment options for the anaerobic treatment of domestic wastewater, Rev. Environ. Sci. Biotechnol., 5 (2006) 73–92.

[7] D. Paredes, P. Kuschk, T.S.A. Mbwette, F. Stange, R.A. Muller and H. Koser, New aspects of microbial nitrogen transformations in the context of wastewater treatment – A review, Eng. Life Sci., 7(1) (2007) 13–25.

[8] M.J. Hammer and M.J. Hammer, Jr., Advanced wastewater treatment, in Water and Wastewater Technology, 4th ed., Prentice – Hall Inc., New Jersey, 2000.

[9] S. Philips, H.J. Laanbroek and W. Verstraete, Origin, causes and effects of increased nitrite concentrations in aquatic environments, Rev. Environ.l Sci. Biotechnol., 1 (2002) 115–141.

[10] K.K. Roeleveld and G. Zeeman, Anaerobic treatment in decentralized and source — separation-based sanitation concepts, Rev. Environ. Sci. Biotechnol., 5 (2006) 115–139.

[11] E. Larsson and J. Persson, Viability of membrane bioreactor technology as an advanced pre-treatment for onsite wastewater treatment, Thesis submitted for fulfillment of Master of Science Program, Luleå University of Technology, Department of Civil and Environmental Engineering, Division of Sanitary Engineering, 2004, pp. 1–147.

[12] C. Visvanathan, L.N. Thu, V. Jegatheesan and J. Anotai, Biodegradation of pentachlorophenol in a membrane bioreactor, Desalination, 183 (2005) 455–464.

[13] S. Velizarov, J.G. Crespo and M.A. Reis, Removal of inorganic anions from drinking water supplies by membrane bioprocesses, Rev. Environ. Sci. Biotechnol., 3 (2004) 361–380.

[14] E. Wasik, J. Bohdziewicz and M. Blaszczyk, Removal of nitrate ions from natural water using a membrane bioreactor, Separ. Purif. Technol., 22–23 (2001) 383–392.

[15] K.H. Ahn, K.G. Song, E. Cho, J. Cho, H. Yun, S. Lee and J. Kim, Enhanced biological phosphorous and nitrogen removal using a sequencing anoxic/anaerobic membrane bioreactor (SAM) process, Desalination, 157 (2003) 345–352.

[16] J. Grundestam and D. Hellstrom, Wastewater treatment with anaerobic membrane bioreactor and reverse osmosis, Water Sci. Technol., 56(5) (2007) 211–217.

[17] Z. Ahmed, B.R. Lim, J. Choo, K.G. Song, K.P. Kim and K.H. Ahn, Biological nitrogen and phosphorous removal and changes in microbial community structure in a membrane bioreactor: Effect of different carbon sources, Water Res., 42 (2008) 198–210.

[18] W. Yang, N. Cicek and J. Ilg, State-of-the-art of membrane bioreactors: Worldwide research and commercial applications in North America, J. Membr. Sci., 270 (2006) 201–211.

[19] W.Q. Han, L.J. Wang, X.Y. Sun and J.S. Li, Treatment of bactericide wastewater by combined process chemical coagulation, electrochemical oxidation and membrane bioreactor, J. Hazard. Mater., 151(2–3) (2007) 306–315.

[20] L. Chu, X. Zhang, F. Yang and X. Li, Treatment of domestic wastewater by using a microaerobic membrane bioreactor, Desalination, 189 (2006) 181–192.

[21] O.T. Komesli, K. Teschner, W. Hegemann and C.G. Gokcay, Vacuum membrane applications for domestic wastewater reuse, Desalination, 215 (2007) 22–28.

[22] B.Q. Liao, J.T. Kraemer and D.M. Bagley, Anaerobic membrane bioreactors: Applications and research directions, Crit. Rev. Environ. Sci. Technol., 36 (2006) 489–530.

[23] J.H. Choi, K. Fukushi, H.Y. Ng and K. Yamamoto, Evaluation of a long-term operation of a submerged nanofiltration membrane bioreactor (NF MBR) for advanced wastewater treatment, Water Sci. Technol., 53(6) (2006) 131–136.

[24] P. Artiga, E. Ficara, F. Malpei, J.M. Garrido and R. Mendez, Treatment of two industrial wastewaters in a submerged membrane bioreactor, Desalination, 179 (2005) 161–169.

[25] K. Kimura, M. Enomoto and Y. Watanabe, Modification of submerged membrane bioreactors (MBRs) by inserting baffles: pilot scale study, Water Sci. Technol., 55(7) (2007) 119–126.

[26] K. Kimura, R. Nishisako, T. Miyoshi, R. Shimada and Y. Watanabe, Baffled membrane bioreactor (BMBR) for efficient nutrient removal from municipal wastewater, Water Res., 42 (2008) 625–632.

[27] C. Wei, X. Huang and X. Wen, Pilot study on municipal wastewater treatment by a modified submerged membrane bioreactor, Water Sci. Technol., 53(9) (2006) 103–110.

[28] F.I. Hai, K. Yamamoto and K. Fukushi, Different fouling modes of submerged hollow-fiber and flat-sheet membranes induced by high strength wastewater with concurrent biofouling, Desalination, 180 (2005) 89–97.

[29] E. Germain and T. Stephenson, Biomass characteristics, aeration, oxygen transfer in membrane bioreactors: Their interrelations explained by a review of aerobic biological processes, Rev. Environ. Sci. Biotechnol., 4 (2005) 223–233.

[30] J.H. Ho, S.K. Khanal and S. Sung, Anaerobic membrane bioreactor for treatment of synthetic municipal wastewater at ambient temperature, Water Sci. Technol., 55(7) (2007) 79–86.

[31] R. Canziani, V. Emondi, M. Garavaglia, F. Malpei, E. Pasinetti and G. Buttiglieri, Effect of oxygen concentration on biological nitrification and microbial kinetics in a cross-flow membrane bioreactor (MBR) and moving-bed biofilm reactor (MBBR) treating old landfill leachate, J. Membr. Sci., 286 (2006) 202–212.

[32] C.Y. Chang, J.S. Chang, Y.W. Lin, L. Erdei and S. Vigneswaran, Quantification of air stripping and biodegradation of organic removal in acrylonitrile-butadiene-styrene (ABS) industry wastewater during submerged membrane bioreactor operation, Desalination, 191 (2006) 162–168.

[33] D. Jeison, Anaerobic membrane bioreactors for wastewater treatment — Feasibility and potential applications, PhD thesis, Wageningen University, Wageningen, The Netherlands, 2007.

[34] A. Saddoud, M. Ellouze, A. Dhouib and S. Sayadi, Anaerobic membrane bioreactor treatment of domestic wastewater in Tunisia, Desalination, 207 (2007) 205–215.

[35] E. Kocadagistan and N. Topcu, Treatment investigation of the Erzurum City municipal wastewaters with anaerobic membrane bioreactors, Desalination, 216 (2007) 367–376.

[36] B. Rezania, J.A. Oleszkiewicz and N. Cicek, Hydrogen-dependent denitrification of water in an anaerobic submerged membrane bioreactor coupled with a novel hydrogen delivery system, Water Res., 41 (2007) 1074–1080.

[37] Y.T. Ahn, S.T. Kang, S.R. Chae, C.Y. Lee, B.U. Bae and H.S. Shin, Simultaneous high-strength organic and nitrogen removal with combined anaerobic upflow bed filter and aerobic membrane bioreactor, Desalination, 202 (2007) 114–121.

[38] A. Beaubien, M. Baty, F. Jeannot, E. Francoer and J. Manem, Design and operation of anaerobic membrane bioreactors: development of a filtration testing strategy, J. Membr. Sci., 109 (1996) 173–184.

[39] Metcalf and Eddy, Wastewater Engineering: Treatment and Reuse, 4th ed., Mc-Graw Hill, New York, 2002.

[40] N. Cicek, A review of membrane bioreactors and their potential application in the treatment of agricultural wastewater, Canad. Biosystems Eng., 45 (2003) 6.37–6.46.

[41] S. Delgado, F. Diaz, R. Villaroel, L. Vera, R. Diaz and S. Elmaleh, Nitrification in a hollow-fibre membrane bioreactor, Desalination, 146 (2002) 445–449.

[42] L.M. Yuan, C.H. Zhang, Y.Q. Zhang, Y. Ding and D.L. Xi, Biological nutrient removal using an alternating of anoxic and anaerobic membrane bioreactor (AAAM) process, Desalination, 221 (2008) 566–575.

[43] J.K. Kim, I.S. Song, H.S. Oh, J.H. Park and Y.K. Choung, Removal of nitrogen and organic matter in swine wastewater by using membrane bioreactor and advanced oxidation process, 8th IWA

Specialized Conference on Small Water and Wastewater Systems (SWWS) and 2nd IWA Specialized Conference on Decentralised Water and Wastewater International Network (DEWSIN), Coimbatore, India, 2008, pp. 96–103.

[44] C. Visvanathan, R. Ben Aim and K. Parameshwaran, Membrane separation bioreactors for wastewater treatment, Crit. Rev. Environ. Sci. Technol., 30(1) (2000) 1–48.

[45] L. Chu, X. Zhang, F. Yang and X. Li, Treatment of domestic wastewater by using a microaerobic membrane bioreactor, Desalination, 189 (2006) 181–192.

[46] C. Visvanathan, N.Q. Hung and V. Jegatheesan, Hydrogenotrophic denitrification of synthetic aquaculture wastewater using membrane bioreactor, Process Biochem., 43(6) (2008) 673–682.

[47] G.T. Seo, T.S. Lee, B.H. Moon, J.H. Lim and K.S. Lee, Two stage intermittent aeration membrane bioreactor for simultaneous organic, nitrogen and phosphorous removal, Water Sci. Technol., 41(10–11) (2000) 217–225.

[48] Z. Ujang, M.R. Salim and S.L. Khor, The effect of aeration and non aeration time on simultaneous organic, nitrogen and phosphorous removal using an intermittent aeration membrane bioreactor, Water Sci. Technol., 46(9) (2002) 193–200.

[49] Water Environment Federation (WEF), Membrane Systems for Wastewater Treatment, McGraw Hill, New York, 2006.

[50] F. Fatone, D. Bolzonella, P. Battistoni and F. Cecchi, Removal of nutrients and micropollutants treating low loaded wastewaters in a membrane bioreactor operating the automatic alternate-cycles process, Desalination, 183 (2005) 395–405.

[51] C.B. Ersu, S.K. Ong, E. Arslankaya and P. Brown, Comparison of recirculation configurations for biological nutrient removal in a membrane bioreactor, Water Res., 42(6–7) (2008) 1651–1663.

[52] C. Abegglen, M. Ospelt and H. Siegrist, Biological nutrient removal in an small-scale MBR treating household wastewater, Water Res., 42 (2008) 338–346.

[53] M.C. Ramphao, M.C. Wentzel, G.A. Ekama and W.V. Alexander, A comparison of BNR activated sludge systems with membrane and settling tank solid-liquid separation, Water Sci. Technol., 53(12) (2006) 295–303.

[54] E.J. McAdam and S.J. Judd, A review of membrane bioreactor potential for nitrate removal from drinking water, Desalination, 196 (2006) 135–148.

[55] U. Bracklow, A. Drews, M. Vocks and M. Kraume, Comparison of nutrients degradation in small scale membrane bioreactors fed with synthetic/domestic wastewater, J. Hazard. Mater., 144 (2007) 620–626.

[56] H.H. Chen, S. Shiau and Y.C. Lin, Membrane bioreactor application in wastewater re-use from the effluent of Bali primary WWTP, Northern Taiwan, Water Sci. Technol., 53(9) (2006) 131–140.

[57] J. Cho, K.G. Song, S.H. Lee and K.H. Ahn, Sequencing anoxic/anaerobic membrane bioreactor (SAM) pilot plant for advanced wastewater treatment, Desalination, 178 (2005) 219–225.

[58] N.I. Galil and Y. Levinsky, Sustainable reclamation and reuse of industrial wastewater including membrane bioreactor technologies: case studies, Desalination, 202 (2007) 411–417.

[59] K. Zhang, H. Choi, M. Wu, G.A. Sorial, D. Dionysiou and D.B. Oerther, An ecology based analysis of irreversible biofouling in membrane bioreactors, Water Sci. Technol., 55(8) (2007) 395–402.

[60] P. Le-Clech, V. Chen and T.A.G. Fane, Review — Fouling in membrane bioreactors in wastewater treatment, J. Membr. Sci., 284 (2006) 17–53.

[61] S. Liang, C. Liu and L. Song, Soluble microbial products in membrane bioreactor operation: Behaviors, characteristics and fouling potential, Water Res., 41 (2007) 95–101.

[62] N. Jang, X. Ren, K. Choic and I.S. Kim, Comparison of membrane biofouling in nitrification and denitrification for the membrane bioreactor (MBR), Water Sci. Technol., 53(6) (2006) 43–49.

[63] X. Li, F. Gao, Z. Hua, D. Gu and J. Chen, Treatment of synthetic wastewater by a novel MBR with granular sludge developed for controlling membrane fouling, Separ. Purif. Technol., 46 (2005) 19–25.

[64] Y. Yeo, N. Jang, J. Cho, K.S. Kim and I.S. Kim, Identification of the effect of extracellular polymeric substances on bacterial adhesion to the membrane surface in a membrane bioreactor using *Pseudomonas flourescens*, Water Sci. Technol., 55(1–2) (2007) 35–42.

[65] A. Ramesh, D.J. Lee and J.Y. Lai, Membrane biofouling by extracellular polymeric substances or soluble microbial products from membrane bioreactor sludge, Appl. Microbiol. Biotechnol., 74 (2007) 699–707.