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Membrane bioreactor technology for decentralised wastewater treatment

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MEMBRANE BIOREACTOR TECHNOLOGY FOR DECENTRALISED WASTEWATER TREATMENT AND REUSE

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ABSTRACT

Driven by stricter environmental regulations and legislation on wastewater discharge and shrinking fresh water resources, water treatment has become an area of significant concern while at the same time there is a growing interest in utilising non-traditional water resources by means of water reclamation and water recycling. Amongst the many treatment alternatives emerged recently, membrane bioreactors (MBRs) have been seen as an effective technology capable of transforming various types of wastewater into high-quality effluent exceeding most discharge requirements and suitable for a variety of reuse applications. Despite the potential to provide decentralised small scale water reuse systems at an apartment block or an individual household level, to date, MBRs are largely restricted to centralised large scale applications, with the most common capacity of 200 ML per day or above. The aim of this paper is to review and discuss the potential and limitations of MBRs for small scale applications. Both technical and economic considerations will be delineated with respect to the future water outlook in Australia. Particular attention is also given to the impact of MBR technology on the removal of micropollutants that are of significant concern in water recycling.

KEY WORDS

Membrane bioreactors, membrane filtration, decentralised wastewater treatment, water recycling, trace contaminants.

INTRODUCTION

Increasing demand for water, drought and water scarcity have now been a common issue facing many urban and rural communities around the world. Water recycling is a pragmatic and sustainable approach for many countries to relieve or solve these problems on water supplies. It can be divided into two categories, internal domestic or industrial recycling, and external recycling where the discharge from a sewage works is used for aquifer recharge or irrigation. Amongst the many treatment alternatives emerged recently for water recycling, membrane bioreactor (MBR), which combines membrane filtration and biological process for wastewater treatment, is one of the most widely applied technologies especially at a large scale municipal wastewater treatment. This is probably due to the many advantages such as small footprint, high effluent quality and high performance in trace organic removal for safe and environmentally benign discharge that MBR can offer. The reclaimed water could be used in a wide range of non-portable water reuse applications such as toilet flushing and irrigation. Due to the robustness and modular nature of the technology, MBRs can also be a potential technology for wastewater treatment and reuse at a decentralised level such as in a large building, cluster of houses or even in the individual houses. This paper will review and discuss the possibility of MBRs application and limitations in terms of technical and economics for small scale domestic wastewater treatment and reuse.

MEMBRANE BIOREACTORS (MBRs)

Definition

Combining a biological reactor with membrane filtration, MBR is a preferable technology for many water recycling applications as it retains all the inherent advantages of both processes. The membrane prevents the loss of biological solids and high molecular weight organic solutes from the bioreactor and thus maintaining a high biomass concentration and enhancing the mineralisation of influent organic matter. As a result of membrane separation, solids retention time (SRT) is independent of hydraulic retention time (HRT). Consequently, MBR can offer very high quality effluent suitable for discharge into environmentally sensitive areas as well as can be used in a range of water recycling applications. MBR also has a potential to treat hard organics such as pharmaceutically active compounds (PhACs) which are designed to be quite persistent to induce the required medical effects prior to metabolisation in the body of the recipients. In addition to the enhanced biodegradation effect, the membrane may also be an effective barrier for the removal of certain trace organics, particularly when nanofiltration (NF) membranes are used [1, 2] instead of microfiltration (MF) and ultrafiltration (UF) membranes.

Configurations

MBRs can be applied in two configurations as shown in Figure 1, namely side-stream (or external membrane) and submerged membrane systems. In the former, the membrane is installed externally to the reaction vessel. This allows a better access to the membrane for cleaning, maintenance, and can substantially reduce the risk of membrane fouling. In the latter, the membrane is installed within the reaction vessel; therefore, eliminate the need for extra energy consumption to recirculate the activated sludge and space for an additional vessel. Submerged MBR system was developed in the mid 1990s and have been applied widely in municipal wastewater treatment since it requires lower power costs than the external MBR configuration (due to the absence of a high-flow recirculation pump). On the other hand, the external configuration was considered to be more suitable for industrial wastewater treatment as a result of its capacity to tolerate the harsh and highly variable industrial wastewater often characterised by elevated temperature, high organic strength, extreme pH, high toxicity and low filterability [3]. Consequently, one would expect that the submerged configuration is more suitable for decentralised treatment and reuse of domestic wastewater.

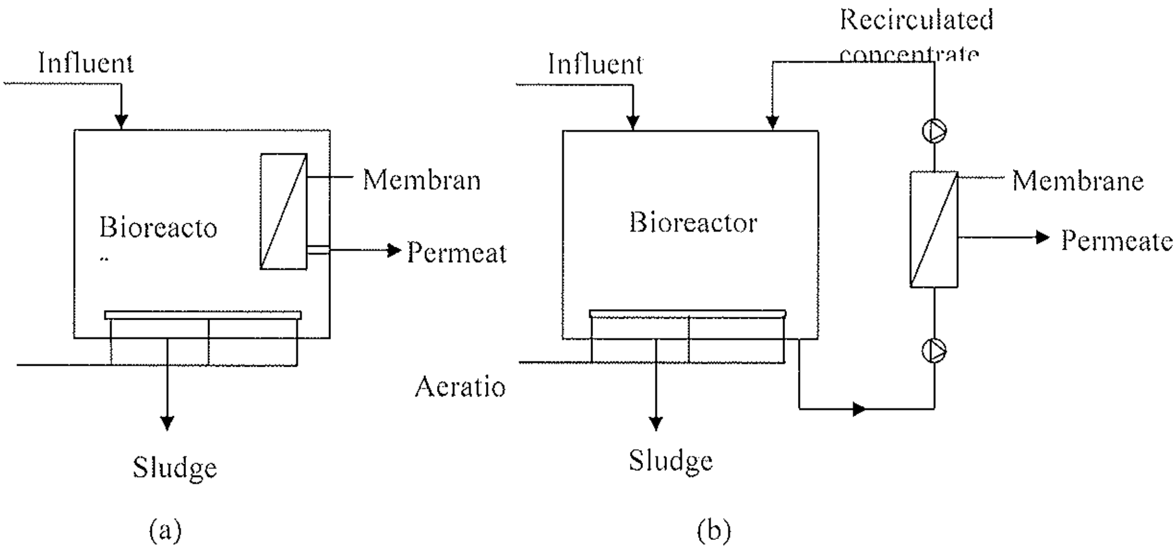

Figure 1: Schematic of the two common membrane bioreactor configurations (a) submerged MBR; (b) side-streamed MBR

Key operating parameters

Flux and aeration

Although a primary objective of aeration is to provide the oxygen required for the biodegradation of organic matter and to maintain a uniform distribution of biomass throughout the reactor, in the submerged configuration, it also helps to control fouling by creating turbulence and scouring effect along the membrane surface [4]. This additional benefit of aeration is particularly important for submerged MBRs as they are more susceptible to membrane fouling [5]. In a typical MBR set up, air is introduced below membrane and is distributed to optimize the air scouring action across the membrane surface [6].

Hydraulic retention time

The hydraulic retention time (HRT) affects the operation of MBR process. Chang et al. [7] reported the effect of HRT on biomass concentration, removal efficiency and permeate flux of long-term operation of submerged MBR. The results indicated that the HRT considerably affected the MLSS concentration with a HRT of 18 h leading to the highest biomass concentration (approximately 35 g/L). However, when considering removal efficiency of MBR, it was found that minimal effect of HRT on organic removal in terms of BOD, COD and TOC. Also, they found that at lower HRT operation, membrane cleaning by using chemicals was required.

Sludge retention time

Sludge retention time (SRT) is a parameter which indicates the mean residence time of microorganisms in the reactor. Longer SRT in MBR process can maintain high biomass concentration and thus higher sludge digestion. Therefore, the sludge production is approximately 50% less than that of an activated sludge process [8]. SRT influences the operation performance of MBR process. Grelier et al. [9] found that SRT of 40 days provided the best performance of immersed MBR with the lowest fouling rate. This study suggested the better performance at the sludge retention time ranges from 15 to 40 days. Also, Lee et al. [10] reported the effect of SRT on microfiltration and membrane fouling. The result indicated that overall fouling resistance increased as SRT increased from 20 to 60 days. In addition, achievement of effluent concentration of a certain compound is dependent on the selected/operated SRT. For example, Clara et al. [11] found that operating SRT at higher than 10 days yielded low effluent concentrations of micropollutants for MBR process.

Potential of MBRs

MBR systems have mostly been used to treat industrial and municipal wastewater where stringent discharged standards are applied. As can be seen in Table 1, MBR is superior over the conventional activated sludge treatment process with regard to removal efficiencies of almost all of the bulk water quality parameters including total suspended solids, turbidity, biochemical oxygen demand (BOD), chemical oxygen demand (COD), dissolved organic carbon (DOC) and pathogenic organisms. Furthermore, a high organic loading rate can be applied in MBRs, which enable a longer sludge retention time (SRT) and hence subsequently reduces sludge production (Table 2). Over all, this enhances the capacity of MBRs to remove solids, organic matter, nutrients (nitrogen and phosphorous) [12], and a potential to mineralise trace organics such as pharmaceutically active compounds (PhACs) and endocrine disrupting chemicals (EDCs) [13, 14], some of which can be classified as hard organics. At the same time, this also alleviates the need for regular sludge withdrawal and hence eases maintenance requirements to some extent.

Table 1: Removal efficiencies comparison between MBRs and activated sludge (AS) [15-17]

Parameter	Membrane bioreactor	Activated sludge
TSS, mg/L	>99	60.9
Turbidity, NTU	98.8-100	85-95
COD, mg/L	89-98	94.5
BOD, mg/L	>97	85-95
DOC, mg/L	96.9	92.7
NH_3-N, mg/L	80-99	98.9
Total coliforms, CFU/100mL	5-8 log	Not available
Faecal coliforms, CFU/100mL	Non-detectable	2.34
Bacteriophages, CFU/100 mL	>3.8	1.31

Table 2: Comparison of sludge production by various wastewater treatment processes [18]

Treatment process	Sludge production (kg/ kgBOD)
Submerged MBR	0.0-0.3
Structured media biological aerated filter (BAF)	0.15-0.25
Trickling filter	0.3-0.5
Conventional activated sludge	0.6
Granular media BAF	0.63-1.06

Applications

Municipal or domestic wastewater treatment is both the earliest and largest application for MBRs [19]. According to Yang et al. [3], most of the ongoing MBRs plants which are operated in North America are medium-scale or small-scale with the largest number of applications for capacity of less than 100 m^3/d. This demonstrates that the application of MBRs for on-site decentralised system is possible and can offer the most advanced wastewater treatment options in low-density areas at a cost lower than that of conventional large-scale pipe-and-plant systems. In small communities, houses are spread out, the population density is low and hence the use of an on-site system for an individual home or for a cluster of homes would be a cost-effective option. This issue in terms of cost consideration will be reviewed in the next section. In fact, while MBR applications at the individual or cluster household level are currently limited, the effectiveness of this approach for greywater recycling in a single commercial building or sporting venue have recently been demonstrated [20].

WATER RECYCLING UTILISING MBR TECHNOLOGY

Decentralised water recycling

While exploitation of new water resources such as seawater desalination is still a preferred short-term option by some authorities, a gradual but permanent reduction in per capita water use through socially acceptable means is widely recognised by all stakeholders in the water industry as the strategic long term sustainable solution to address the on-going water shortage currently experienced by many countries. However, the cost of large-scale water recycling applications remains high and often uneconomical due to the need to overhaul the existing water distribution systems. Large-scale water recycling applications are currently restricted mostly to green field development projects such as the Rouse Hill project in Western Sydney where recycled water is supplied in a separate pipe. Furthermore, there is a significant risk of cross-connection associated with the dual-reticulation network, which can seriously dampen public support. While the implementation of the large-scale water recycling is expected to take many years, decentralised water recycling can be applied much more readily. In fact, decentralised wastewater management is not a new concept. It can be defined as the collection, treatment and disposal/reuse of wastewater from individual dwellings, clusters of homes or isolated communities, industries or institution facilities [21]. It is noteworthy that traditional decentralised treatment systems such as septic tanks were in the past widely used to treat small quantities of wastewater. However, a major obstacle of decentralised water recycling remains the lack of a suitable technology that can meet the unique criteria required for small-scale water treatment. Some essential requirements are high and reliable treated effluent quality, robustness, tolerance to variable contaminant loading, small footprint, and ease of operation and maintenance. Given the significant development of the membrane filtration technology over the last two decades, these requirements can likely to be met by the use of MBRs. It is expected that MBRs can contribute to a significant increase in decentralised water reclamation/reuse activities.

Small-scale MBRs for wastewater treatment

Decentralised MBRs processes can play an important role in wastewater treatment to satisfy a range of technical and economic criteria. Not surprisingly, in Australia alone small scale MBR systems for greywater recycling at a single household level have been marketed by several companies such as AquaCell in New South Wales and BushWater in Queensland. It is, however, surprising to note that there is currently very limited information exists with regards to long performance of these systems. In practice, the MBR is usually coupled with other unit operations to achieve the necessary performance goals. Figure 2 is a generic flow sheet of wastewater treatment for reuse with membrane processes described by Fane and Fane [22]. This shows a pre-treatment step (possibly screening) prior to the membrane bioreactor followed by either oxidative or UV post treatment to yield water for reuse.

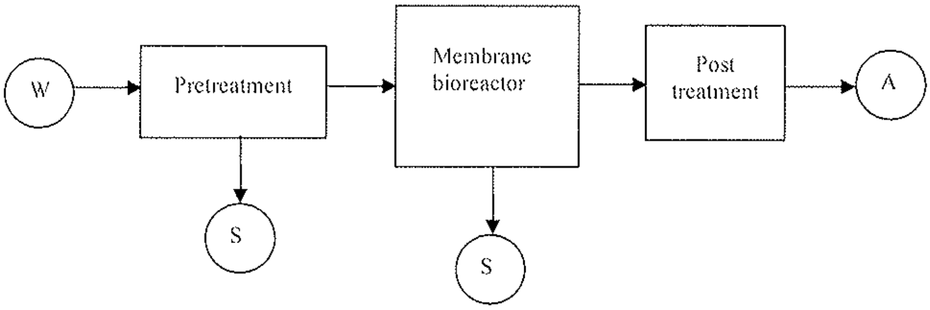

Figure 2: Generic view of domestic wastewater treatment for reuse with membrane processes. A= high quality water; S= Solids; W=Wastewater (Adapted from [22]).

Advantages of MBRs for decentralised treatment

Key advantages of MBRs for decentralised wastewater treatment and reuse include high and reliable treated effluent quality, small footprint, and high tolerance to variable contaminant loading. Due to the modular nature of MBRs, small scale MBRs can retain the superiority over conventional treatment methods such as septic tanks with regards to effluent quality, which has been very well documented in the literature [22]. It is also noteworthy that MBRs can be easily combined with other complementary treatment technologies such as UV disinfection and pre-screening, which can further enhance the robustness of the treatment system and hence make it particularly suitable for water recycling applications. Smaller footprint and smaller reactor volume is one of prominent advantages of MBR. MBR processes are able to maintain higher MLSS concentration of up to 25,000 mg/L during municipal wastewater treatment compared to activated sludge process with limitation of sedimentation process resulting in lower biomass concentration. This advantage led to the volume of bioreactor reduction and thus footprint. For example, a MBR applied to treat greywater with a capacity of 500 m^3/d in the Mori building, Tokyo was found to save the equivalent area as 25 car parking places compared to traditional treatment process [23]. The ability of MBRs to resist a significant variation in contaminant loading of the influent has also been demonstrated. Oliver et al [24] found that the performance of a bench scale MBR system can be recovered after a significant perturbation which involved the introduction of 1000 mg/L of hypochlorite to the feed.

Limitations of MBRs for decentralised treatment

A key factor limiting the economic viability of MBRs is the fouling of the membrane surface by pollutant species. The fouling increases the hydraulic resistance of the membrane and thus increases the energy demand for membrane permeation and/or declining the permeate flux [25]. Although fouling can be suppressed by operation at a lower membrane flux, the membrane area requirement is increased, and substantially removed by cleaning with backwashing and /or chemical. Both increase the overall process cost and cleaning also leads to an undesirable chemical load on the waste stream. More importantly, membrane fouling entails a cumbersome maintenance requirement which can be seen as a major drawback of small scale MBR applications.

High capital cost can also be seen as another limitation of small scale MBRs although currently there is very little information to substantiate this premise. Friedler and Hadari [20] analysed the economic feasibility of on-site greywater reuse systems in buildings based on MBR systems. They found that on-site MBR systems became feasible when it is used for the treatment of wastewater incorporating several buildings together because cost is sensitive to building size. Therefore, the on-site MBR system for single building seems to be unfeasible. This is a limitation of decentralised MBR systems. However, the true cost of water supply which takes into account the externalities of resource depletion was not used in their analysis. Furthermore, it is expected that as the demand for decentralised MBRs increase and the membrane technology continue to develop, the use of on-site MBRs can be cost-competitive in the near future.

TRACE ORGANIC REMOVAL IN DECENTRALISED MBR TREATMENT

Trace organic removal by MBRs

The enhanced separation attributed to the use of MF or UF membranes has resulted in an excellent pathogenic removal by MBRs with log removal reported varied between 6-8 log scale for bacteria and 3-5 log scales for virus. Consequently, MBR effluents were found to be compliant with some of the most stringent discharge requirement and for certain non-portable reuse applications. However, the removal efficiencies of MBRs with respect to trace organic contaminants remain largely unknown. A large number of these trace contaminants including endocrine disrupting chemicals (EDCs), pharmaceuticals and their residuals, pesticides, and other industrial chemicals have been detected in wastewater and effluent impacted water bodies at trace level typically in the range of several micrograms per liter (μg/L) or lower. There has also been a substantial body of evidence that they may induce a negative impact on humans and wildlife. Examples of these include the ferminization of freshwater fish [26] or the increase incidence of antibiotic resistance bacteria. While recycled water is currently not intended for direct human consumption, there is a heightened concern amongst the scientific community and the public about the possible adverse environmental effects induced by a continuous flow of these trace contaminants. Not surprisingly, a considerable number of dedicated scientific investigations has been devoted to this subject. As summarized in Table 3, a wide range of trace contaminants commonly found in municipal wastewater has been investigated. However, it is prudent to note that fate and occurrence of trace contaminants in a decentralized context (or household level) can be erratic and quite different from that of centralized municipal source as to a large extent they depend on the behaviour and lifestyle pattern of the individuals in the household.

Removal mechanisms

Several researchers have reported enhanced removal effect of some trace organic contaminants by MBRs compared to conventional activated sludge systems [13, 27, 28]. It can be hypothesized that the enhanced removal efficiency is a direct result of a higher biomass concentration and a longer sludge retention time that can be achieved in a typical MBR system. Furthermore, this enhanced removal effect can also be attributed to the adsorption of the hydrophobic trace organics to the sludge and the subsequent enhanced sludge retention by the membranes. It is noteworthy that this is probably not attributed to the additional retention of the unadsorbed compounds due to size exclusion when MF or UF membranes are used as these trace organics are typically much smaller than the membrane pore size. However, as summarised in Table 3, the removal of trace organics by MBRs vary significantly from almost zero to complete elimination, depending on the actual target compounds and perhaps the MBR systems used. To some extent, this highlights the role of the physicochemical properties and the degradation constant of the individual compounds examined in such studies.

The enhanced biodegradation due to a longer sludge retention time (SRT) has been identified as a major advantage of MBRs over conventional activated sludge systems. Removal of several hydrophobic compounds has been reported to be positively correlated to the sludge retention time (SRT), with an SRT of at least 10 days being needed to achieve effective removal [11, 29]. While a 10 day SRT can be practically achieved in a centralized conventional activated sludge treatment plant, due to space limitation, this becomes impractical in a decentralized context. In contrast, a small scale MBR system can be operated at almost any SRT.

Table 3: The performance of MBRs in removal of trace contaminants

Trace contaminant	MBR	Types of Wastewater	Removal efficiency (%)	References
Estradiol Estrone	Hollow fibre MF-MBR	Municipal wastewater	Approx 100	[30]
Naproxen Ketoprofen Bezafibrate Ibuprofen Diclofenac	Submerged MBR (Kubota plate & frame membranes)	Municipal wastewater	53-89 41-83 87-95 >99 7-53	[31]
Bisphoenol A Nonylphenol	Submerged hollow fibre UF-MBR	Municipal wastewater	~ 92-99 ~ 81	[32]
Roxithromycin Sulfamethoxazole Iopromide Diclofenac Ibuprofen Naproxen Carbamazepine Galaxolide Tonalide	MF or UF MBR	Municipal wastewater	Not reported 0 Not reported 20-40 >90 50-80 0 <50 <50	[33]
17 β-estradiol (E2) 17 α-ethinylestradiol Bisphenol A Benzophenone Clofibric acid Gemfibrozil Ibuprofen Fenoprofen Ketoprofen Naproxen Diclofenac Indomethacin Propyphenazone Carbamazepine	Hollow fibre MF-MBR	Artificial wastewater	~99 60-75 50-99 60-75 0-38 5-95 30-95 20-95 10-70 0-85 10-95 30-80 0 5-25	[14]
2,4-dichlorophenol	Activated carbon coupled with MBR	A synthetic wastewater	>98.99	[34]
Carbamazepine Phenazone Propy-phenazone Formylaminoanti-pyrin (FAA) 17 β-estradiol Estrone 17 α-ethinylestradiol	Submerged MBR	Municipal wastewater	0-4 15-72 11-75 11-65 >94 >95 80-95	[35]
Ibuprofen 2,4-dichlorobenzoic acid Diclofenac Clofibric acid Carbamazepine	Submerged MBR	Municipal wastewater	99 83 58 54 13	[36]
Ibuprofen Bezafibrate Diclofenac Tonalide Galaxolide 17 α -ethinyl estradiol	UF-MBR	Municipal wastewater	77-95 97-100 0-40 80 80 10-80	[27]
Clofibic acid Diclofenac Ibuprofen Ketoprofen Mefenamic acid Naproxen Dichloprop (herbicide)	Hollow-fibre MF-MBR (submerged)	Municipal wastewater	Not quantitatively reported	[13]

Adsorptive interaction between trace organics and biomass is another major factor influencing the removal efficiency of these compounds. In fact, low removal efficiencies of compounds such as sulfamethoxazole, carbamazepine, and propyphenazone can be attributed to their polar nature with a low hydrophobicity. In other words, they have low adsorptive capacity to the sludge. In contrast, effective removal efficiencies of hydrophilic compounds such as natural hormones, nonylphenols, and bisphenol A were consistently reported (Table 3). For several other acidic pharmaceuticals (such as clofibric acid, ibuprofen, and ketoprofen), Urase et al. found that the removal efficiencies of these compounds depended strongly on the solution pH, which was explained by the speciation of the compounds [14]. As these compounds speciate, they can change their behaviour from highly adsorptive (when they are neutral) to non-adsorptive (when they are negatively charged). This can probably also explain the significant variation in removal efficiencies of trace organic contaminants reported in the literature. It should also be noted that experiments leading to the results summarised in Table 3 were not conducted under the same conditions.

CONCLUSIONS

This review illustrates that MBRs can be a particularly useful technology for decentralised wastewater treatment and reuse. Given the small footprint and robustness of the technology, it is expected that MBRs will make a considerable contribution to promote small scale water recycling. With regards to most bulk water quality parameters including microbiological parameters, MBR's treated effluent is typically suitable for discharge into environmentally sensitive areas as well as a range of water recycling applications. However, several challenging obstacles still remain that may limit wide spread applications of MBRs at a small scale. Most important of which are membrane fouling and the subsequent maintenance requirement and the high capital cost of the technology. The technology also has a potential to treat hard organics such as EDCs, pharmaceuticals and their residuals, although further research is still needed to identify the underlying removal mechanisms and to optimise the removal efficiency.

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